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Impact of Lube Oil on Advanced Light-Duty CIDI Engine Emissions

INTERIM REPORT

TFLRF No. 351

by

Dr. Kent Froelund
Edwin C. Owens
Janet P. Buckingham
Edwin A. Frame
U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
San Antonio, TX 78228

Under Contract to

U.S. Army TARDEC
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The Partnership for a New Generation of Vehicles (PNGV) has identified the compression-ignition, direct-injection (CIDI) diesel enigne as a promising technology in meeting the PNGV goal of an 80-mpg, production prototype, mid-size sedan by 2004. Challenges remain in reducing emission levels of the CIDI engine to meet future emissions standards. Techniques under consideration for this project include the use of an alternative fuel (ADMM15) and the use of different lubricants. The objective of this program was to perform an initial screening of three different lubricants to obtain information on their contribution to the particulates emitted by the engine and the potential for emission reduction in a CIDI engine.

14. SUBJECT TERMS

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EXECUTIVE SUMMARY

Background and Objectives: The Partnership for a New Generation of Vehicles (PNGV) has identified the compression-ignition, direct-injection (CIDI) diesel engine as a promising technology in meeting the PNGV goal of an 80-mpg, production-prototype, mid-size sedan by 2004. Challenges remain in reducing emissions levels of the CIDI engine to meet future emissions standards. Techniques under consideration for this project include the use of an alternative fuel (ADMM15) and the use of different lubricants. The objective of this program was to perform an initial screening of three different lubricants to obtain information on their potential for emission reduction in a CIDI-engine.

Technical Approach: The Department Of Energy (DOE) and the CRC initiated this testing to determine the emissions contribution of various oil formulations in a CIDI engine. The emissions testing was performed utilizing a DaimlerChrysler OM 611 diesel engine. This engine is a 2.2L, turbo-charged with inter-cooling, direct-injection, diesel equipped with a high-pressure, common-rail fuel injection system. It also has variable-EGR and variable intake swirl capacity. No adjustments were made to the engine operating parameters to account for various fuel and lubricant properties. The test conditions were thus run with constant-torque settings.

Three lubricants were used for the evaluation, a mineral based SAE 5W-30, a synthetic SAE 5W-30 with similar viscosity characteristics but lower volatility, and a synthetic SAE 15W-50 which has volatility similar to the synthetic 5W-30, but higher viscosity throughout the temperature range. Two test fuels were used, a California certification fuel (CARB) and a low-sulfur low-aromatic fuel containing 15 percent dimethoxymethane (ADMM15). This latter oxygenated fuel has been shown to be a low particulate forming fuel in other studies [2].

The test sequence consisted of five steady-state speed and load points and one FTP heavy-duty transient test. The steady-state conditions were selected to span a wide range of engine operations, and are consistent with the steady-state conditions selected for previous programs. The transient test, although a heavy-duty test with a predominance of high-power conditions, was selected since it is a widely recognized dynamometer-based transient cycle. The test sequence was repeated three times for each fuel and oil in a randomized test matrix. For each test mode, regulated emissions of total particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and total hydrocarbons (HC) were measured. To investigate the composition of the particulate in further depth, the total particulate was fractionated into the fuel volatile organic fraction (Fuel-VOF), oil volatile organic fraction (Oil-VOF), and the residual non-volatile organic fraction (Non-VOF).

Results

At most modes, the interaction between oil and fuel variables on emissions was not significant, thus allowing independent consideration of the fuel and oil effects.

Compared to the CARB fuel, ADMM15:

- reduced the average total particulate mass emissions by 42 percent, with all the PM reduction in the non-volatile portion of the particulate,
- reduced the average CO emissions by 19 percent,
- reduced the average hydrocarbon emissions by 33 percent,
- increased the average NO_x emissions by 12 percent,
- and at most conditions had no significant effect on CO_2.

Independent of the fuel effects on emissions, the lubricant differences also produced statistically significant variations in engine-out emissions. The particulate mass was fractionated by a gas chromatographic technique into non-volatile portion (non-VOF), a fuel-like volatile portion (fuel-VOF), and an oil-like volatile fraction (oil-VOF).

- The fuel-VOF was independent of lubricant.
- At low power conditions, non-VOF was independent of lubricant. However, at the higher power modes (14 and 17) and the transient operations, use of the synthetic 15W-50 lubricant appeared to increase the non-VOF mass.
- Since the fraction of the particulate that is volatile decreases with increasing engine BMEP, oil variation has a greater effect at low power conditions. At mode 10, a point representative of light duty driving cycle operations, the oil contribution represented 40 percent of the total PM at the worst case combination of low PM forming fuel (ADMM15) and high PM forming lubricant (mineral 5W-30).
- At most operating modes, the lubricant variations had a statistically significant impact not only on PM, but also on NO_x, CO, CO_2, and unburned hydrocarbons.

Conclusions

Lubricant formulation makes a significant contribution to engine particulate emissions, which increases in importance as fuel-derived emissions are reduced. At low power, light duty cycle operations the lubricant contribution to PM is predominately in the volatile fraction. The data developed here suggests that at high power, heavy duty cycle operations the lubricant may have a significant contribution to the non-volatile portion of the PM.

Lubricant formulation changes can reduce the oil-VOF portion of the PM, and through changing the engine frictional losses also have a significant impact on NO_x and CO_2 emissions.

FOREWORD/ACKNOWLEDGMENTS

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The authors would like to acknowledge the assistance provided by Mr. Lothar Schmid, Mr. Uwe Knauke, and Mr. Horst Hanauer all of DaimlerChrysler, Stuttgart, Germany for supplying the engine and for their technical support for this testing program. Mr. Ricky Frierson and Mr. R. De La Cruz of SwRI's Department of Emissions Research (DER) performed the emissions testing under the supervision of Mr. Mike Starr.

The CRC Industrial Leaders, Dr. Spyros Tseregounis of GM R&D, and Dr. Andrew Jackson of ExxonMobil R&E, are also offered thanks for their leadership of the project, along with Dr. Jim Wallace III, who provided strategic direction throughout the project execution.

Finally, the authors would also like to acknowledge the assistance provided by Ms. Wendy Mills in report preparation.

TABLE OF CONTENTS (contd)

LIST OF TABLES

LIST OF ILLUSTRATIONS

SYMBOLS AND ABBREVIATIONS

ADMM15	15% Dimethoxymethane, 85% Low-Sulfur, Low-Aromatic Diesel
ALS	Alternative Low Sulfur
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
ASSYST	Mercedes Proprietary Oil Conditioning System
bhp	Brake Horse Power
BMEP	Brake Mean Effective Pressure
CARB	"pseudo" California Reference Fuel
CIDI	Compression Ignition, Direct Injection
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COTR	Contracting Officer's Technical Representative
CRC	Coordinating Research Council
DENOX	Nitrogen Oxide After-Treatment Device
DFI-GC	Direct Filter Injection Gas Chromatography
DMM	Dimethoxymethane
DOE	Department of Energy
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FID	Flame Ionization Detector
FMEP	Friction Mean Effective Pressure
FTP	Federal Test Procedure
HC	Hydrocarbon
ICP	Coupled Plasma Emission Spectroscopy Method
IMEP	Indicated Mean Effective Pressure
LEL	Lower Explosion Limit
NOACK	Evaporative Measure for Oils
NO_x	Nitrogen Oxides
OC	Oil Consumption
PM	Particulate Matter
PNGV	Partnership for a New Generation of Vehicles
RPM	Revolutions per Minute
SI	Spark Ignition
SwRI	Southwest Research Institute
TARDEC	Tank-Automotive Research Development and Engineering Center
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
UTLF	Upper Temperature Limit of Flammability
VOF	Volatile Organic Fraction
ZDDP	Zinc Dialcyl Dithio Phosphate

1.0 INTRODUCTION

As part of a growing interest in the performance and emissions benefits of advanced, compression-ignition direct-injection (CIDI) engines, the Partnership for a New Generation of Vehicles (PNGV) is investigating the benefits of small CIDI engines. When coupled with an alternative/reformulated fuel, the CIDI engine has the potential to contribute significantly to the PNGV goal of developing an environmentally friendly mid-size car with triple the fuel efficiency of today's cars.[1]*

Previous studies have demonstrated the emissions benefit of reformulated and alternative diesel fuels.[2] However, engine particulate emissions include a contribution from the lubricant. As the fuel contribution to particulate matter (PM) decreases, the lubricant can be an increasingly important factor in meeting emissions regulations. This project was to quantify the lubricant contribution to PM emissions and assess the potential for reducing the impact of lubricating oil on the emissions.

For this project, engine-out exhaust emissions mappings were conducted for two fuels and three lubricants utilizing a DaimlerChrysler OM 611 CIDI engine. The engine is a 2.2L, direct-injection diesel, with a high-pressure, common-rail fuel injection system. The engine design is similar to the specifications of the PNGV target CIDI engine.

The common-rail fuel injection system has been shown to have great potential in reducing exhaust emissions and noise. [6] The OM 611 engine utilizes some of the most advanced design features, which will be incorporated into other commercially produced diesel engines in the near future. However, it should not be assumed that the results of this project indicate the lowest emissions possible in diesel engines with the selected fuels. However, some general sensitivity to changes in fuels and oils can be expected in other CIDI engines.

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*Numbers in brackets indicate references at the end of the document.

Triplicate tests were performed for each fuel and oil combination to increase the statistical strength of the data set. Five steady-state conditions and the FTP Heavy-Duty Transient cycle were selected by the Lube Oil Steering Group. These conditions were selected to maintain consistency across PNGV projects. For each fuel and oil, the engine was operated at constant torque.

2.0 OBJECTIVE

1. The primary objective is to determine the contribution of lubricant oil to engine-out particulate matter (PM) in advanced diesel engines. Part of this investigation will determine whether commercially available synthetic engine oil can significantly reduce the mass of the volatile organic fraction (VOF) of the particulate.

2. A secondary objective is to determine whether changes in engine oil result in changes in other criteria emissions such as NO_x.

3.0 TECHNICAL APPROACH

3.1 Test Engine

The emissions test was conducted with the 1997 Mercedes Benz 2.2 L, direct-injection, turbodiesel engine. This engine was chosen because it is an early production implementation of a turbocharged and intercooled, common-rail, direct-injection diesel engine, and it is currently applied in Mercedes Benz C220 TD vehicles. [6-7]

The following are some relative benefits of this concept:

- Lower noise since pilot injection quantities can be controlled
- Higher low-speed torque
- Freely selectable fuel injection pressures with better fuel preparation even at low-power conditions

The specifications of this engine are described in Table 1. A cross-sectional drawing is provided in Figure 1, and a cross-sectional drawing in the longitudinal direction is provided in Figure 2. The engine is characterized by a high specific torque for engines of similar type and of the same model year. This torque is achieved over a wide range of engine speeds by control of turbocharging boost pressure.

The engine is a four-cylinder, in-line block design. The cylinder block is made of grey cast iron, and the cylinder head is of aluminum.

Table 1. Engine Specifications

Displacement	2.2L
Bore	88 mm
Stroke	88.4 mm
Compression Ratio	19:1
Diameter Inlet Valve	30.2 mm
Diameter Exhaust Valve	28.4 mm
Max. Torque @ Speed	300 Nm (~220 lb-ft) @ 1600-2600 rpm
Specific Torque	140 Nm/l
Rated Power @ Speed	92 kW (125 hp) @ 4200 rpm
Specific Power	42.3 kW/l
BMEP	17.5 bar
Max. Injection Pressure	1350 bar (~19600 psi)
Max. Ignition Pressure	140 bar
Min. BSFC	203 g/kW-hr
Oil SAE Grade	15W40

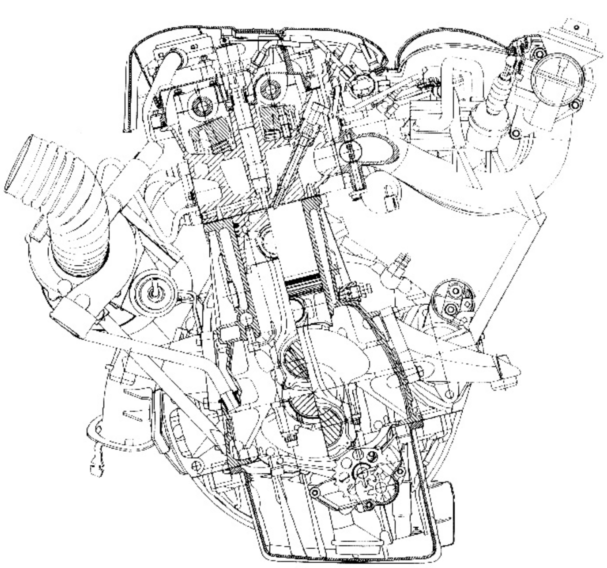

Figure 1. Cross-Section View Of Engine

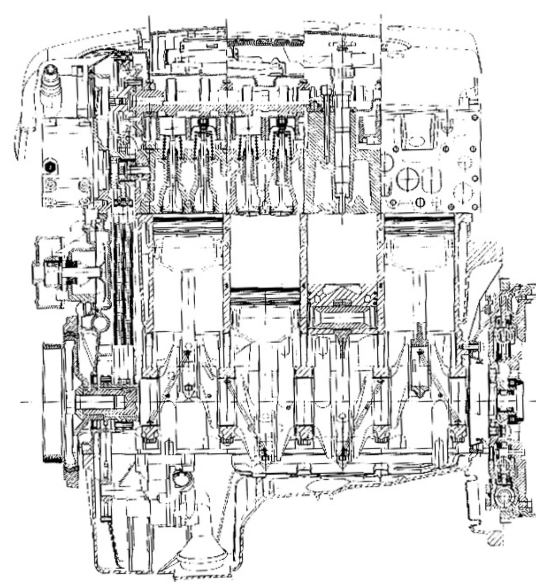

Figure 2. Longitudinal Cross-Section of Engine

Because the common-rail injection system leaves little free space, the oil in the blow-by gases is separated by means of a splash plate (larger droplets) and a spiral separator (finer droplets), in which the oil is returned to the oil chamber in the crankcase via a long siphon.

3.2 Engine Setup

The broken-in engine (Serial Number: 611691-30-112390) was set up in a transient test cell at Southwest Research Institute (SwRI) in San Antonio, Texas. Figures 3 through 6 provide pictures of this setup. For the emissions sampling, the exhaust was connected to the particulate tunnel positioned under the roof of the test cell.

Because of the high vapor pressure of ADMM15 fuel, fuel-system modifications were made as in the previous study.[2] The ADMM15 fuel was cooled in an ice bath prior to being supplied to the fuel pump. The internal fuel-heater in the engine was bypassed as well. With these modifications, no fuel problems occurred during the project.

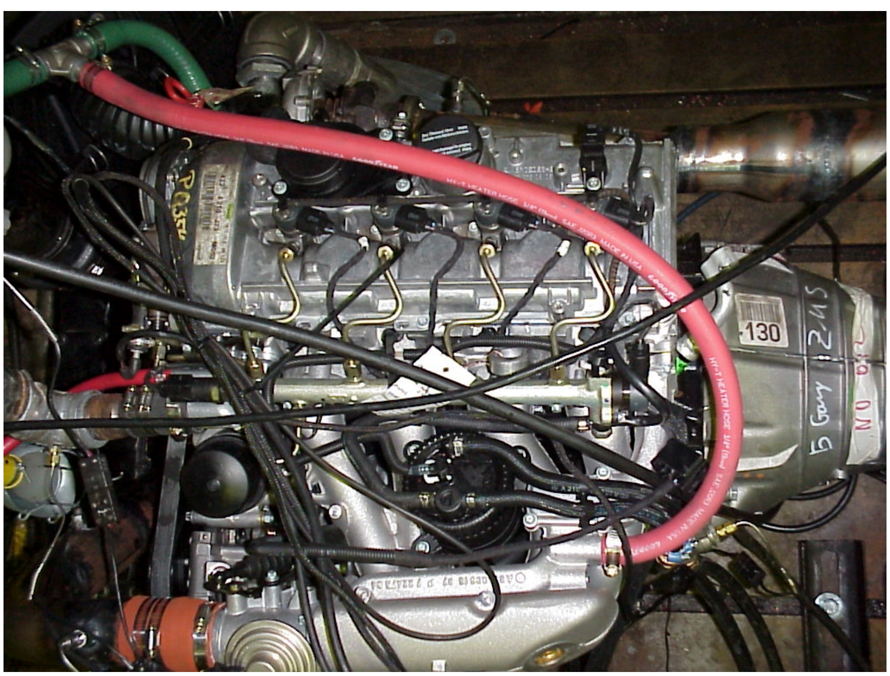

Figure 3. Top View of Mercedes Benz OM 611 Engine Installed in Test Cell

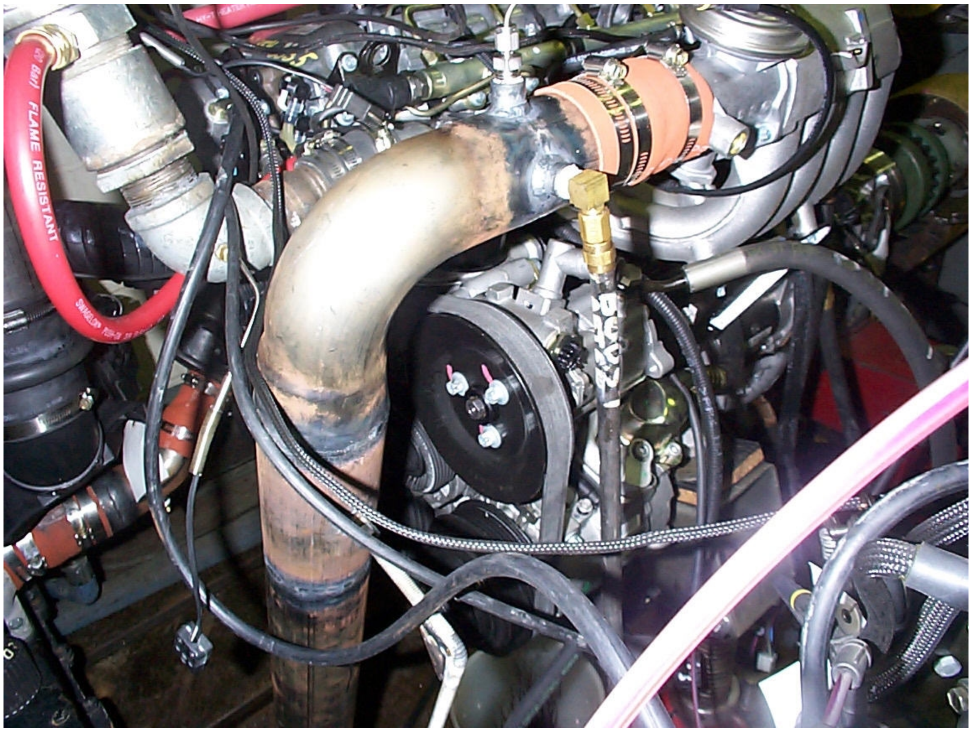

Figure 4. Front View of Mercedes Benz OM 611 Intake Air System

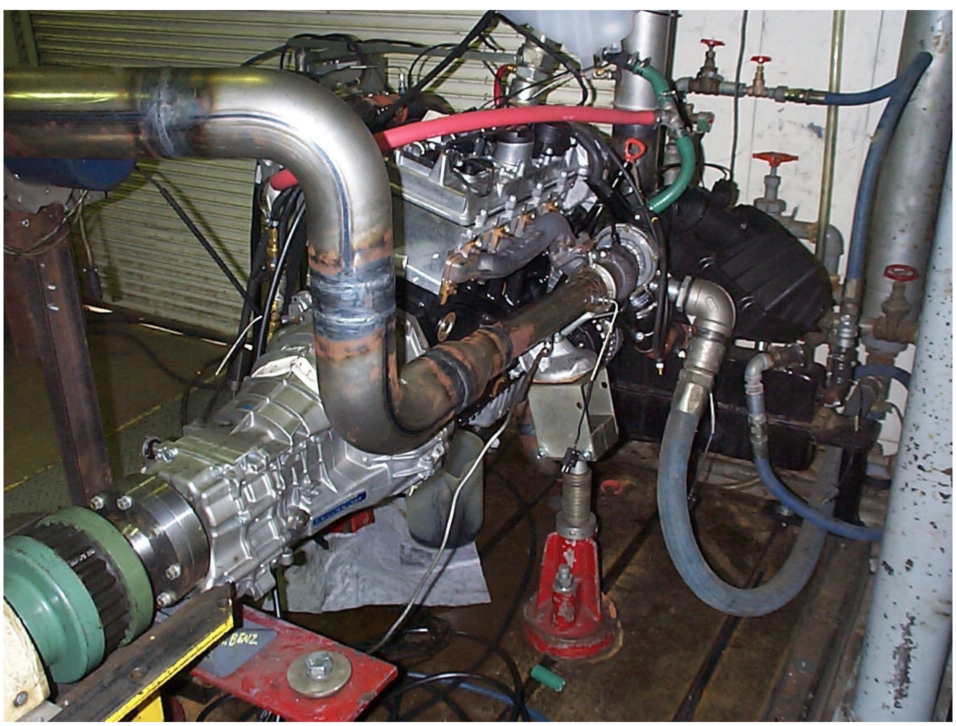

Figure 5. Rear View of Mercedes Benz OM 611 Exhaust System

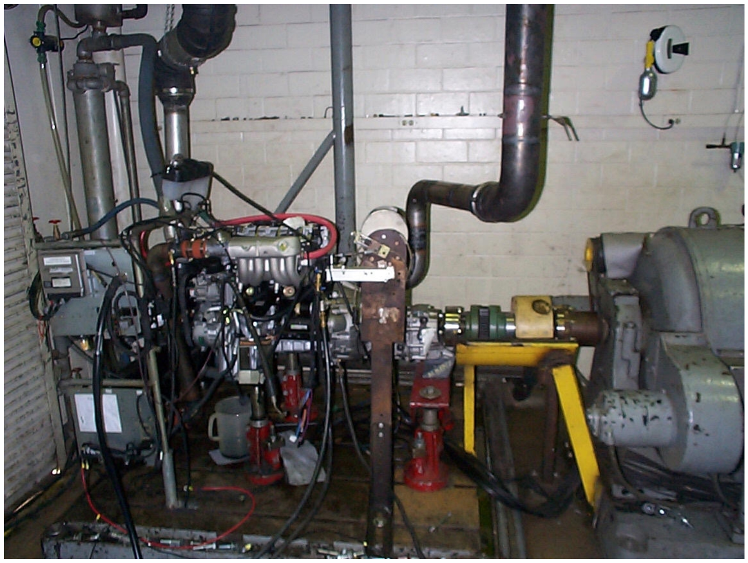

Figure 6. Side View of Mercedes Benz OM 611 Exhaust System

3.3 Emissions Measurement Setup

The dilution tunnel is a partial-flow dilution tunnel. In the primary diluted gas stream, the sampling location can be seen in Figure 7 for the 90-mm filter. Particulate weight measurements are obtained by sampling particulate on 90-mm Pallflex filter media (T60A20). The mass increase of the 90-mm filter, which is conditioned for humidity before and after the test, yields the particulate emissions.

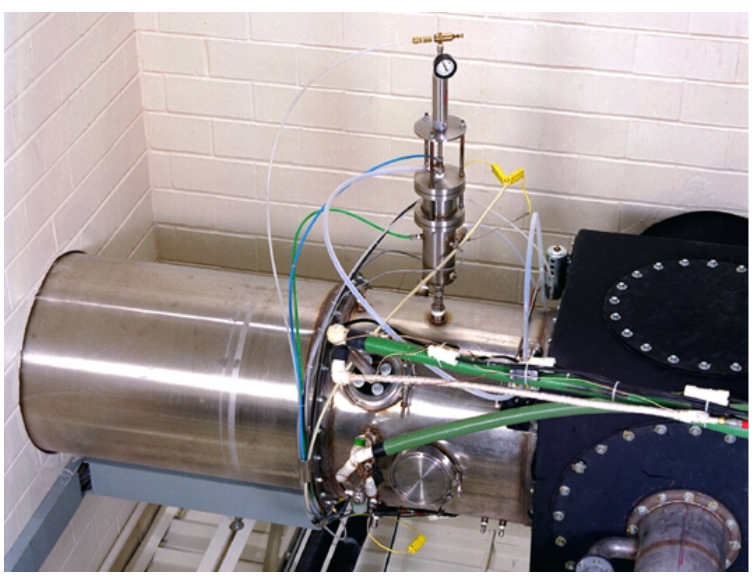

Figure 7. Sampling Location of 90-mm Filter

After weighing, a sample of the particulate mass is fractionated by a SwRI gas chromatographic (DFI-GC) technique (Figure 8 [10]) into non-volatile portion (non-VOF), a fuel-like volatile portion (fuel-VOF), and an oil-like volatile fraction (oil-VOF). The DFI-GC procedure places a portion of the particulate-loaded filter paper directly into the GC, then thermally desorbs volatile material from the particulate mass. The GC column fractionates this volatile portion and detects it by FID at the exit, providing a distribution of eluted material versus retention time (Figure 9). This chromatograph is compared to that of the engine lubricant, and the eluted material is then mathematically partitioned into oil-VOF and a remainder. The remainder is generally considered fuel-derived VOF, although this portion probably is derived from not only fuel but also combustion intermediates and cracked oil as well. The non-volatile fraction is determined by subtracting the sum of the volatile materials from the known mass of total particulate mass. Thus the non-VOF results must be used with caution because of the potential for error stack-up in the calculations.

Forty-seven-mm Fluropore filter media (Figure 10) were used to measure the concentration of additive metals in the particulate mass. Although this technique has been widely used to estimate oil consumption, it has limited measurement resolution.[11,12,13,14,5,15]

Figure 8. Operator Applying Direct Filter Injection Gas Chromatograph (DFI-GC)

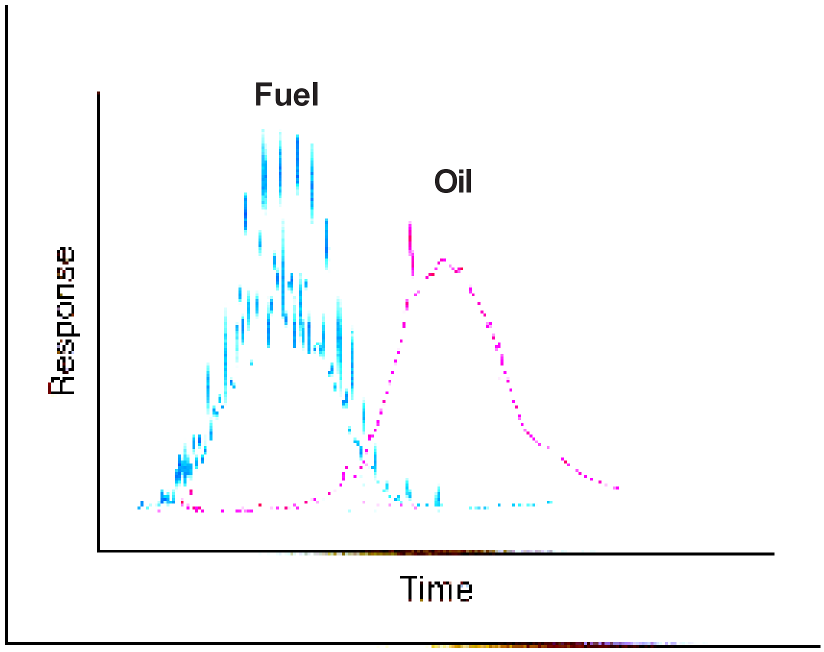

Figure 9. Gas Chromatography of Unburned Oil and Fuel

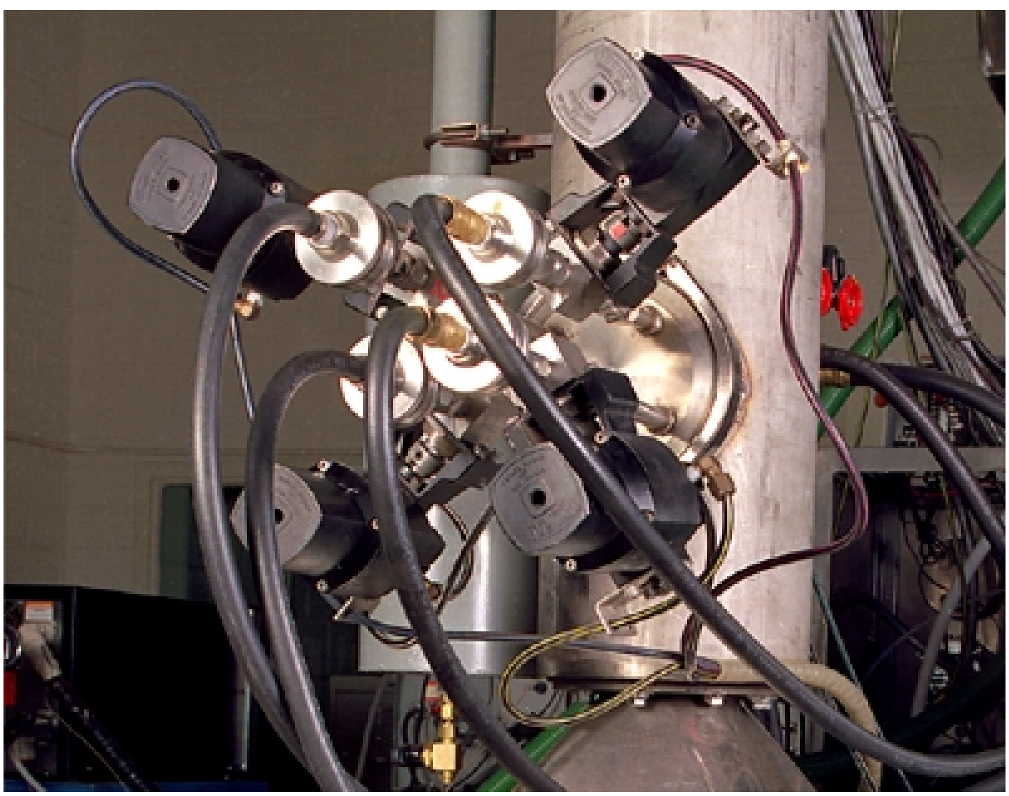

Figure 10. Sampling Location for 47-mm Filter for Estimation of Oil Consumption

3.4 Measured Quantities and Accuracy

The engine was instrumented for measuring the quantities in Table 2.

Table 2. Measured Quantities*

Quantity	Description	Unit	Accuracy
Engine Speed		rpm	+/- 4.2
Engine Load		ft-lb	+/- 2.3
Fuel Flow		lb/hr	+/- 5 %
Temp. Coolant In		°F	+/- 4
Temp. Coolant Out		°F	+/- 4
Temp. Oil		°F	+/- 4
Temp. Intake Air		°F	+/- 4
Temp. Fuel		°F	+/- 4
Temp. Exhaust		°F	+/- 25
Temp. Intercooler In		°F	+/- 4
Temp. Intercooler Out		°F	+/- 4
Temp. Air Dewpoint		°F	+/- 4
Pres. Ambient		"Hg	+/- 1%
Pres. Exh. Restriction		"Hg	+/- 1%
Pres. Boost Pre-Intercooler		"Hg	+/- 1%
Pres. Boost Post-Intercooler		"Hg	+/- 1%
Carbon Monoxide	CO	g/bhp-hr	+/- 15 %
Hydrocarbon	HC	g/bhp-hr	+/- 20 %
Nitric Oxides	NO_x	g/bhp-hr	+/- 10 %
Carbon Dioxide	CO_2	g/bhp-hr	+/- 10 %
Particulate (Total)	PM	g/bhp-hr	+/- 20 %
Fuel-Volatile Fraction of Particulate	Fuel-VOF	g/bhp-hr	+/- 30 %
Oil-Volatile Fraction of Particulate	Oil-VOF	g/bhp-hr	+/- 30 %
Non-Volatile Fraction of Particulate	Non-VOF	g/bhp-hr	+/- 10 %
*Where the accuracy has been found for heavy-duty engines, it has been applied			

3.5 Test Fuels

Exhaust emissions were measured for two fuels (CARB and ADMM15) (Table 3). For this study, the "pseudo" California fuel (CARB) is the baseline fuel against which the emissions of the other dimethoxymethane fuel blend (ADMM15) are compared. ADMM15 is a blend of 15% dimethoxymethane (DMM) with 85% low sulfur diesel (ALS). This fuel provided the largest decrease in particulate formation in a previous SwRI project.[2]

Table 3. Test Fuels					
Property	**ASTM Method**	**Units**	**California Ref. (CARB)**	**Alt. Low Sulfur (ALS)**	**DMM/ALS (ADMM15)**
Density @15°C	D4052	g/ml	0.8378	0.8160	0.8201
Distillation	D2887				
IBP		°C	145	140	58
10%		°C	192	202	179
50%		°C	251	280	273
90%		°C	325	344	344
EBP		°C	372	416	413
Cetane	D613		45	63	59
Cetane Index	D976		48	61	57
Kinematic Vis. @40°C	D445	cSt	2.4	2.9	1.9
Flash Point	D93	°C	72	87	<2(D56)
Composition					
Carbon	D5291	wt%	86.4	85.6	81.6
Hydrogen	D5291	wt%	13.4	14.4	13.7
Oxygen	Difference	wt%	0.2	0.0	4.7
Sulfur	D2622	ppm	176	<10	<10
Chemical					
Aromatics	D5186	vol%	18.9	9.0	8.2*
Paraffins	D2425	vol%		54.5	54.2*
Naphthenes	D2425	vol%		36.9	31.9*
Water	D4928	ppm	105.0	77.0	368.0
Cloud Point	D2500	°C	-27	-4	-7
Pour Point	D976	°C	-32	-5	-9
Acid Number	D664	mgKOH/g	0.02	0.02	0.02
Oxidation Stability	D2274	mg/100ml	0.20	<0.01	0.25
Heat of Combustion	D240	MJ/kg	42.7	43.3	40.8
Lubricity	D6079	mm	0.27	0.57	0.49
BOCLE Scuff	D6078	g	4300	1600	1950
* The DMM is interfering with these results					

3.5.1 CARB Diesel (CARB)

The first fuel labeled CARB in Table 3 is a "pseudo" California reference fuel and is intended to match the performance of a CARB certification fuel as described in the California Code of Regulations.[16] The CARB specification requires a sulfur level below 500 ppm (wt.) and aromatics below 10% (vol.). The CARB fuel used for this project meets the sulfur specification with 176 ppm (wt.), and the aromatics content of 18.9% (vol.).

3.5.2 15% DMM Blend (ADMM15)

The second fuel is a blend of 15% DMM and 85% ALS. DMM ($CH_3O\text{-}CH_2\text{-}OCH_3$) is readily synthesized from methanol and completely miscible in petroleum-based fuels. The ALS fuel is a low-sulfur, low-aromatics fuel with properties comparable to a Swedish class 1, urban diesel fuel.[17] Studies in Europe demonstrated a clear benefit in light-duty emissions with this type of reformulated diesel fuel.[18] ALS has less than 10 ppm sulfur (wt.) and 9% (vol.) aromatics. The cetane number is 61.

Several SwRI reports have shown that DMM effectively reduces particulate emissions when used as an additive in diesel.[2,19] Because pure DMM has a very high vapor pressure, adding DMM drastically lowers the initial boiling point and flash point of the ALS fuel. The 15/85 blend has an initial boiling point of 58°C and a flash point of < 2°C. The blend has an oxygen content of 4.7 wt. % and a slightly lower net heat of combustion than the other hydrocarbon-based test fuel. Because of the DMM blend's volatility, several fuel system modifications were necessary to avoid loss of DMM and vapor formation in hot sections.

3.6 Test Oils

Three oils were selected for this program based on the consensus of the participating partners of this program. These lubricants are formulated from available additives and base stocks. They were selected to give a mix of high and low viscosity and high and low volatility (Table 4).

Table 4. Test Oils

Property	ASTM Method	Unit	M5W30	S5W30	S15W50
SAE Grade		No.	5W30	5W30	15W50
Base Stock		Type	Mineral	Synthetic	Synthetic
Kin. Vis. @ 40°C	D445	cSt	55.8	58.4	123.9
Kin. Vis. @ 100°C	D445	cSt	9.6	10.4	18.5
HTHS	D4683	cP	2.96	3.0*	4.5*
Viscosity Index	D2270	No.	158	169	168
NOACK @ 250°	D5800	Mass %	20.9	7.2	4.9*
Cold Cran. Vis. @ -25°C	D5293	cSt	3120	2350	>3500*
Cold Cran. Vis. @ -15°C	D5293	cSt	N/A	N/A	2420
Concentration of Elementary Elements					
Calcium	D4951	ppm	1260	1560	2538
Phosphorous	D4951	ppm	970	1000	1175
Zinc	D4951	ppm	1070	1070	1315
Sulfur Concentration	D2622	wt.%	0.439	0.250	0.317
*Refers to Typical Values					

3.6.1 5W30 Mineral

The all-mineral-based SAE 5W30 (M5W30) oil was formulated with Group 1 base stocks. This oil was selected to provide high volatility with a NOACK volatility of 20.9%.

3.6.2 5W30 Synthetic

The fully synthetic SAE 5W30 (S5W30) was selected as a reference since it is identical to the 5W30 synthetic formulations used in previous PNGV programs. This lubricant was intended to have high temperature viscosity characteristics similar to the mineral based 5W30, but lower volatility. The NOACK volatility of this oil was 7.2%.

3.6.3 15W50 Synthetic

The third lubricant was a full-synthetic SAE 15W50 (S15W50) oil. This lubricant was selected to have greater high temperature viscosity than the other test lubricants. Its NOACK volatility is 4.9%.

4.0 DESIGN OF EXPERIMENT

A full-factorial experiment was designed with three factors. The three factors and selected levels for testing are:

1. Operating conditions (M20, M10, M5, M17, M14, and transient; see Section 4.1)
2. Fuel (CARB, ADMM15)
3. Oil (Mineral 5W30, Synthetic 5W30, Synthetic 15W50)

The selection of operating conditions is the minimum set of points spanning the engine operating range and is also selected under consideration of consistency across the PNGV program. A composite-weighted, steady-state mode was defined by evenly weighting the emissions from the five steady-state conditions.

The CARB fuel can be thought of as the baseline fuel, whereas the ADMM15 is an oxygenated fuel, which in previous projects was shown to reduce the particulate emissions significantly, typically by 40-50%. The ADMM15 fuel was selected to investigate if the oil contribution increases with reduced fuel contribution to particulate emissions. This will determine if the fuel and oil contribution to particulate emissions is dependent or independent.

The oils were selected so that wide changes in viscosity and volatility could be encountered. The major difference between the M5W30 and the S5W30 oil is the reduction in volatility, and the major difference between the S5W30 oil and the S15W50 oil is the increased viscosity. It is often difficult to uncouple changes in viscosity and volatility since these oil parameters are interconnected (Figure 11 [22]). Both the viscosity and the volatility are known to influence the oil consumption, and thus the particulate emissions. The oil consumption tends to decrease with increasing viscosity (Figure 12 [23]). The viscosity can be changed through the SAE Grade or through the temperature. The oil consumption increases with increasing volatility.

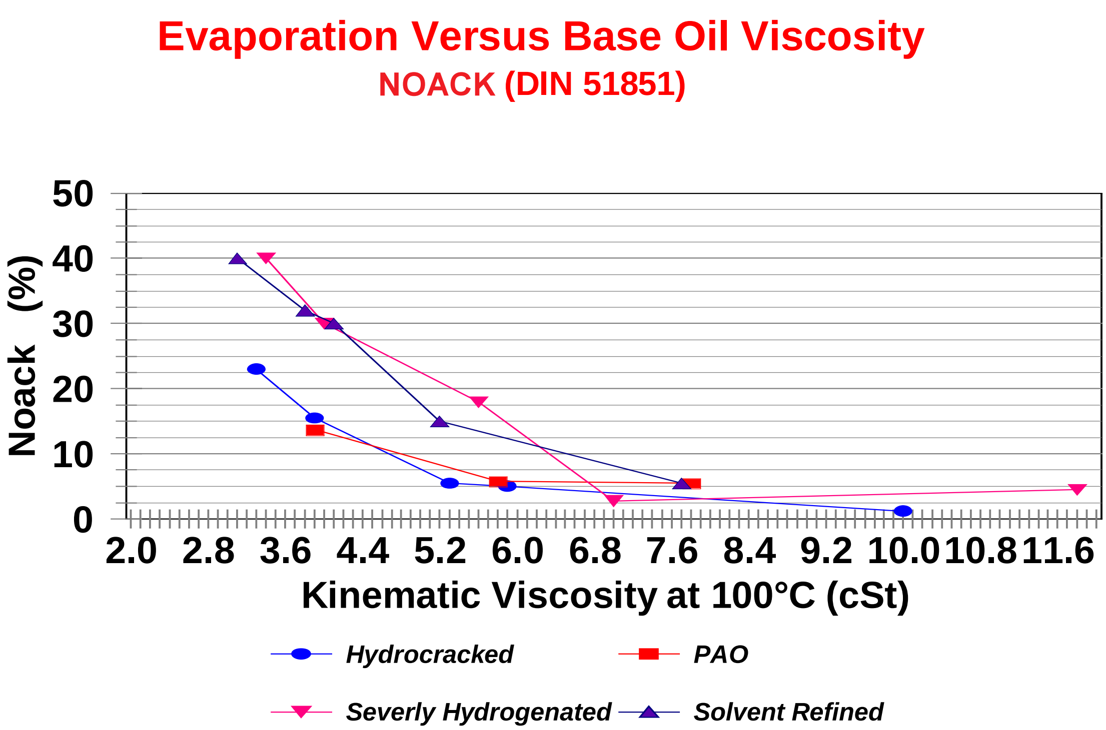

Figure 11. Volatility Versus Viscosity Coupling [22]

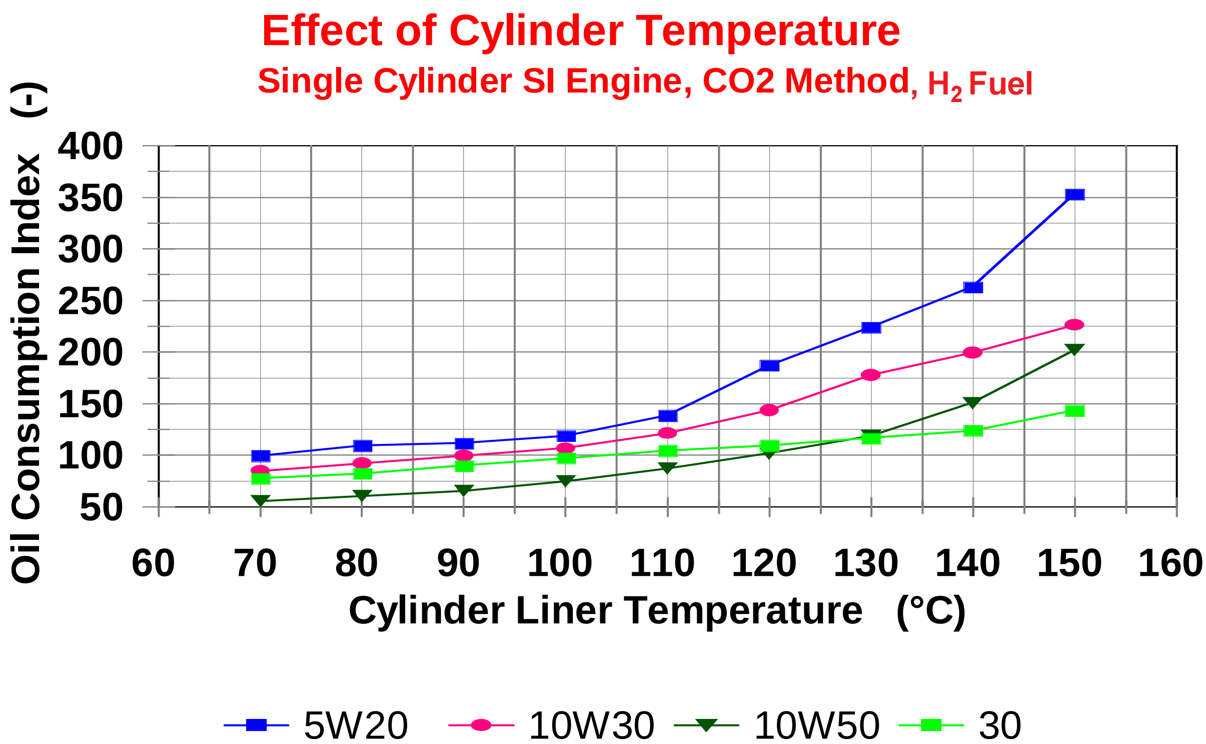

Figure 12. Oil Consumption Versus Mineral Oils of Different SAE Grades [23]

During the experiments, eight response variables were measured:

1. Total Particulate (PM)
2. Non-Volatile Fraction (Non-VOF)
3. Fuel-Volatile Fraction (Fuel-VOF)
4. Oil-Volatile Fraction (Oil-VOF)
5. Nitrogen Oxides (NOx)
6. Carbon Monoxide (CO)
7. Hydrocarbons (HC)
8. Carbon Dioxide (CO_2)

Finally, each test was repeated three times to improve the estimate of experimental variability. The complete test matrix for this project yielded a total of 108 tests (6 conditions x 2 fuels x 3 oils x 3 repeats). Each test combination was assigned an outcome to the eight response variables, resulting in a total of 864 data points created as part of this project. In addition to the test matrix, two baseline repeats were also run in this study.

4.1 Steady-State Operating Conditions

Five operating conditions were selected from a larger set of conditions, which were used in various PNGV programs. Table 5 provides the selected steady-state conditions in tabular form. These conditions were selected to span the speed and load map (Figure 13).

Table 5. Steady-State Test Conditions

Mode	Speed, rpm	Load, ft-lb
M20	1,000	75
M10	2,000	25
M5	2,600	111
M17	2,600	229
M14	4,200	152

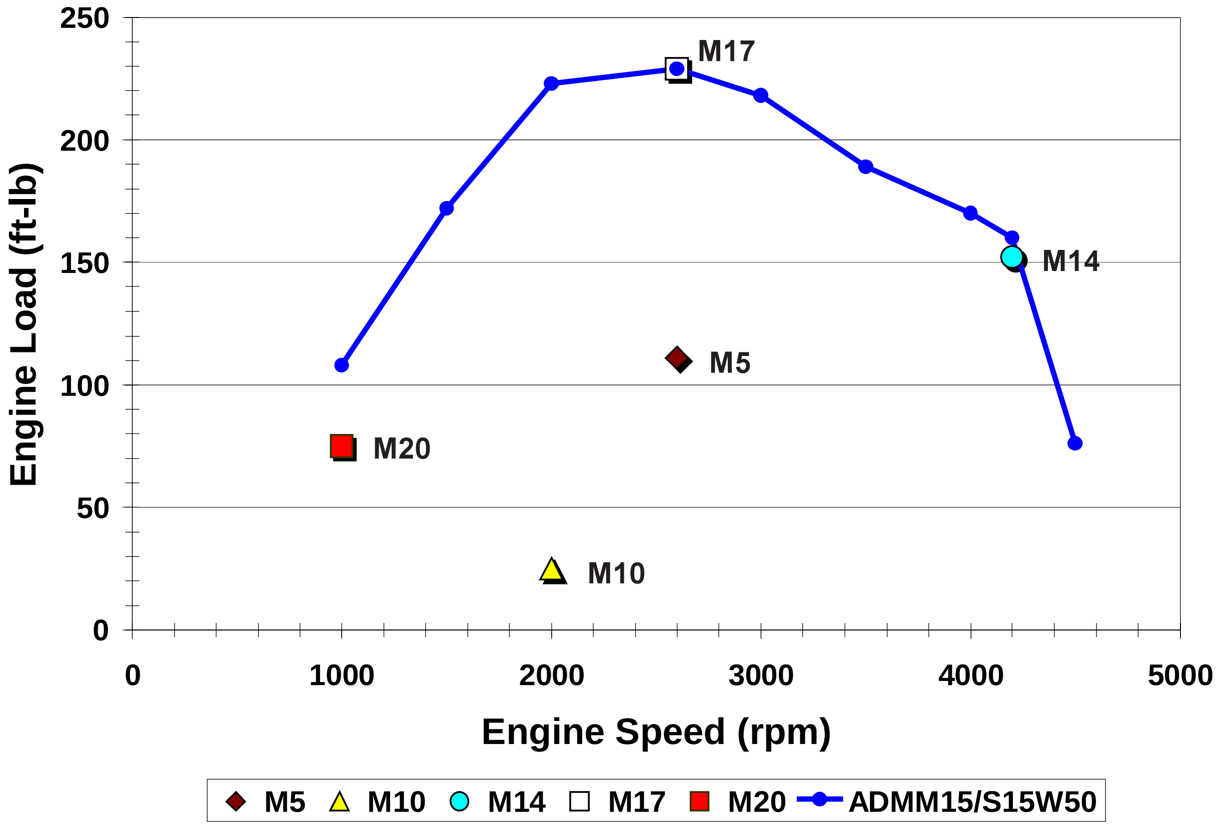

Figure 13. Steady-State Operating Conditions

4.2 Transient Cycle

The U.S. heavy-duty diesel transient procedure was used to investigate any transient effects on the particulate and nitrogen oxide emissions from changing fuels and lubricants (Figures 14 and 15). It was selected since it could be applied on a dynamometer engine setup and is well-standardized within the industry. Since 1984, the EPA has required transient certification for all on-road heavy-duty engines according to this transient cycle. This cycle is characterized by high-power, idle, and negative-load segments. The transient from high-load to low-load is frequently imposing a negative load on the engine (motoring), which is suspected to trigger transient emissions, such as transient oil consumption.

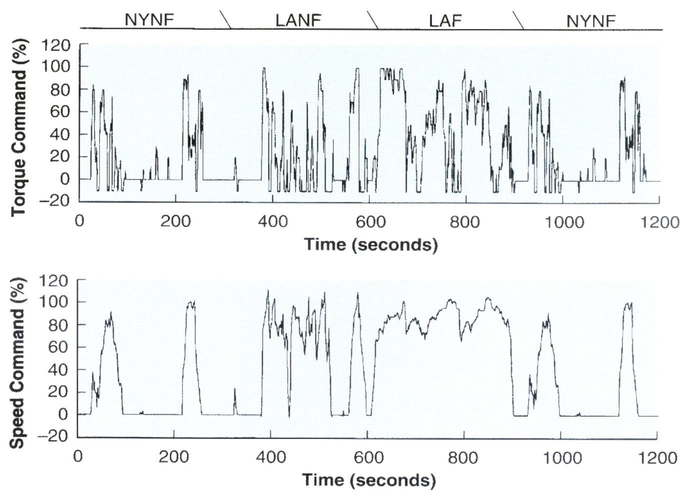

Figure 14. US FTP Heavy-Duty On-Road Transient Cycle

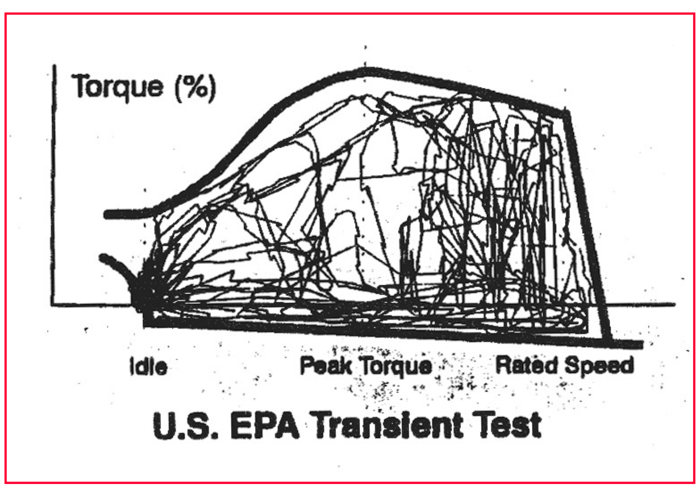

Figure 15. US FTP Heavy-Duty On-Road Transient Cycle

The transient cycle is defined by first defining the full-load curve. All part-load conditions are then normalized relative to the full-load curve. The observed results would be interpreted as, "What is the effect of changing lubricants and fuels on the emissions if this light-duty engine is operated in a way similar to heavy-duty transient operation?"

4.3 Oil and Engine Conditioning Procedure

The lubricant to be tested is received fresh, i.e., unconditioned. Since the effect of lubricants on engine-out particulate and nitric oxide emissions is to be investigated, how the oil is broken-in is extremely important. Literature suggests that higher oil consumption occurs during the first 10-20 hours due to evaporation of volatile light ends.[3,22,24] One reason for this is the distillation process of the front end of the lubricant. If the experiment were initiated without conditioning the lubricant, there was concern that this initial oil volatility would cloud the effect of changing lubricants.

The oil-conditioning procedure consisted of filling the engine with a lubricant (6.0 liter for an oil fill, equal to 1.585 gallon) and operating with the CARB fuel as follows to produce the conditioned oil batch:

- Warm up at idle for 1 min
- Condition Mode 5 (2,600 rpm, 111 ft-lb) for 1 hour
- Condition Mode 16* (3,400 rpm, 177 ft-lb) for 2 hours
- Condition Mode 5 (2,600 rpm, 111 ft-lb) for 1 hour
- Cool down at idle for 1 min

This procedure is repeated with the next oil fill of the same oil until the needed quantity of conditioned oil has been generated for completion of the test plan. The conditioned oil is drained into new and clean 5-gallon buckets and labeled. The different batches of drained oil were mixed so that all condi-

*This condition is not part of the test conditions of this project. It only suits this break-in procedure.

tioned oil can be considered of equal composition. It should be mentioned that the oil conditioning corresponds to 200-300 miles in a field test, which is a small fraction of a typical oil life.

In total, 6 batches of the 5W30 mineral oil, 3 batches of the 5W30 synthetic oil, and 3 batches of the 15W50 synthetic oil were generated, putting 48 hours of additional break-in on the engine. Previous SwRI projects suggest that the engine takes approximately 50 hours to break in (depending on the history of speed and load experienced by the engine). The engine had been broken in by Mercedes Benz for at least two hours at rated power. Therefore, the engine was considered broken-in.

4.4 Test Plan

The test plan was designed considering the time to prepare the engine for the next three-day sequence of tests using another fuel or lubricant. Since it takes considerably longer to flush the fuel than to flush the oil, the test plan contains sequences of tests with the fuel remaining unchanged. Baseline drift of engine emissions and operating parameters is evaluated by including repeat runs of CARB and M5W30. The resulting schedule (Table 6) covers 24 test days, with five steady-state modes and one transient cycle for each test day, plus approximately one working day of preparation time for flushing oil and/or fuel between the experiments.

Details of the fuel-change procedures, oil-change procedures, steady-state preparation procedures, steady-state sequence of modes, and transient run preparation procedures were documented and approved by the clients prior to the experiment.

4.5 Statistical Analysis Methodology

The main objective of the statistical analysis was to determine the effects of engine oil and fuel on the gaseous and particulate emissions. A full-factorial design was completed using the three engine oils and two fuels. All oil and fuel combinations were run in triplicate. This design allowed the examination of the following effects:

Table 6. Test Plan				
Sequence	**Test Day**	**Fuel**	**Oil**	**Nomenclature**
	Conditioning	CARB	Mineral 5W30	
	Conditioning	CARB	Synthetic 5W30	
	Conditioning	CARB	Synthetic 15W50	
1	1 2 = 3 Repeats 3	CARB	Mineral 5W30	CARB/M5W30 (BASELINE)
2	4 5 = 3 Repeats 6	ADMM15	Mineral 5W30	ADMM15/M5W30
3	7 8 = 3 Repeats 9	ADMM15	Synthetic 5W30	ADMM15/S5W30
4	10 11 = 3 Repeats 12	CARB	Synthetic 5W30	CARB/S5W30
5	13 14 = 3 Repeats 15	CARB	Mineral 5W30	CARB/M5W30 (BASELINE)
6	16 17 = 3 Repeats 18	CARB	Synthetic 15W50	CARB/S15W50
7	19 20 = 3 Repeats 21	ADMM15	Synthetic 15W50	ADMM15/S15W50
8	22 23 = 3 Repeats 24	CARB	Mineral 5W30	CARB/M5W30 (BASELINE)

1. Differences among the three engine oils
2. Differences between the two engine fuels
3. Interaction between the engine oil and engine fuel

An analysis of variance (ANOVA) statistical technique was performed using the emissions measurements as the response on the engine oil and fuel factors, in addition to their interaction. As with any classical statistical technique, the assumptions in using ANOVA rely on a particular mathematical model. This model maintains that the "residuals" are independent, identically distributed random variables from a normal distribution with zero mean and equal variance. In all the analyses performed on these data, the ANOVA assumptions were met.

A total of eight statistical analyses were performed. Statistical comparisons were made independently at each of the five steady-state engine-operating modes, the heavy-duty diesel transient mode, and a uniformly weighted composite mode of the five steady-state modes.

All statistical comparisons were made at the 5% level of significance. This is the probability of concluding that there is a difference in the average emissions when in fact there are no differences. This is sometimes called the error rate. In other words, there is a 5% chance that one would conclude the average emissions are different when in reality they are not different. All statistical comparisons are summarized in the tables included in Appendix A. Each table lists the factor effects and its corresponding probability level (p-value). A 5% probability corresponds to a 0.05 p-value. If the p-value for a particular factor is greater than the significance level (0.05), it indicates that there is not sufficient evidence to state that significant differences exist among the average emissions for the particular factor of interest. If the p-value is smaller than the significance level, the evidence is supportive of the statement that there is a significant difference in the average emissions among the factor levels. In statistical terms, the p-value is the smallest level of significance that would result in the decisions to state that there are differences in the average emissions among the factor levels.

If significant factor effects were found, post-hoc multiple comparison tests based on Tukey's Honest Significance Difference (HSD) intervals were computed to determine which factor levels produced statistically significant differences in the average gaseous and particulate emissions. These results are included in Appendix B for each mode and emission analysis. Graphical representations of the ANOVA results are illustrated with Tukey 95% HSD confidence intervals about the average emission for each of the factors tested: oil, fuel, and the interaction between the engine oil and fuel. Overlapping intervals indicate average emissions that are not significantly different at the 0.05 significance level.

Finally, the average values computed by least squares means are included in Appendix C. Averages are computed by engine mode, fuel and oil. These provide a basis for quantifying a change in emissions.

At the industrial leaders' request, the data were analyzed for the effect of engine speed and load on the emissions. This analysis provided similar results to the one calculated as the weighted steady-state mode, which has been included in Appendix A.

5.0 DISCUSSION OF RESULTS

5.1 Engine Operations

A full rack performance test with different fuel and oil combinations was performed to document any differences in maximum torque. The performance data, along with pertinent air and water temperatures for the performance test, are provided in Appendix D.

The testing was conducted according to the test plan until test day 22, the beginning of the final baseline repeat of the CARB, M5W30 case. At that point, the engine suffered a catastrophic turbocharger failure, as documented in Appendix E. Post-failure inspection of the turbocharger found damage to both the compressor and turbine wheels, as well as failure of the connecting shaft. Damage to the compressor rotor appears to have occurred when the retaining nut was spun off by the deceleration of rotation and by impact with the housing, thus focusing attention on the turbine end. The turbine rotor had lost a section of one blade, with the separation occurring at the blade root. Whether this blade failure was due to a problem with the rotor itself, or the result of impact with a foreign body, was uncertain.

Subsequent analysis of the used oil samples taken after each test sequence found substantial increases in wear metal concentrations that began before the last two fuel/oil pairs were tested prior to the failure (Figure 16). Obviously, something was happening prior to the turbocharger failure. The impact that this process had on the emissions and oil consumption is not known.

The engine was then disassembled to determine a source of the wear debris and cause of the failure. There was no internal damage or component failure, nor any apparent cause for the increasing wear debris in the engine oil other than the turbocharger. All valves were intact, the cylinder bore and rings showed no evidence of excessive wear, and all inspected bearing inserts had no visible signs of wear. There was considerable debris in the oil pan and pickup tube screen, which appeared to be from the turbocharger.

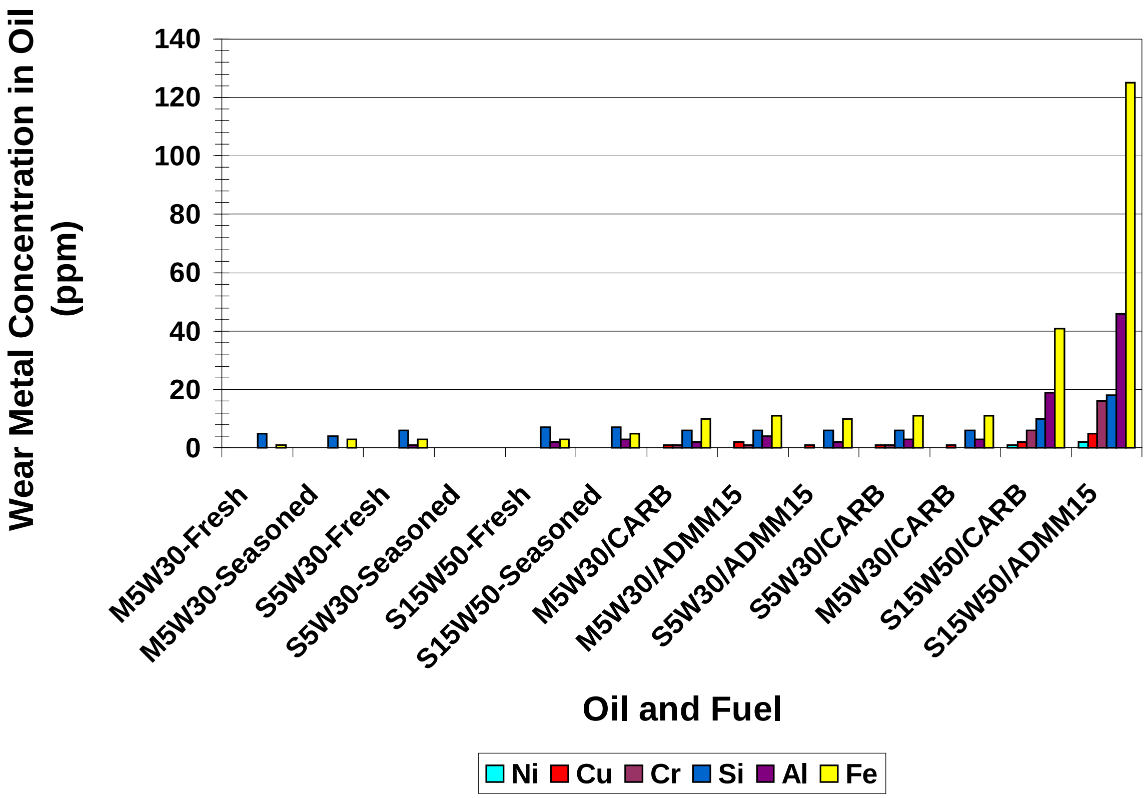

Figure 16. Wear Metal Analysis of Oil Samples

5.2 Engine Emissions Baseline Change

The two sets of (CARB, M5W30) baseline emissions measurements conducted at the beginning and middle of the sequence of tests were examined to determine if there was any change in the engine behavior with time (Table 7).

Table 7. Statistical Comparison of Baseline Tests

	Test Modes*					
Variable	**5**	**10**	**14**	**17**	**20**	**Transient**
PM	⊕	⊕	⊕	⇧	⊕	⊕
NOx	⊕	⊕	⊕	⇩	⊕	⊕
CO	⊕	⇩	⊕	⇧	⊕	⊕
HC	⊕	⊕	⇩	⇩	⊕	⇧

* ⇩ denotes statistically significant decrease,

⇧ denotes statistically significant increase,

⊕ denotes no statistically significant change.

The statistically significant change at the maximum torque, Mode 17 condition, i.e. at 2600 rpm under 100% load, is due to a slight change in air-fuel ratio. This condition is the one with the lowest air/fuel ratio and is thus the condition with the highest sensitivity of particulate emissions to any change in air/fuel ratio. The fuel flow for the repeat testing averaged 41.1 lb/hr, and flow for the first test averaged 39.1 lb/hr. Air flow or air/fuel ratio was not measured as part of this project, but assuming that the air flow did not change, the change in fuel flow would change the air/fuel ratio by up to 5%. This is further supported by the average exhaust temperature increase from 1092°F to 1176°F. After investigating all other measured engine parameters, such as coolant and air temperature, no other changes were observed in the data set.

The engine did not reach the set point for the torque for Mode 17 (maximum torque) or Mode 14 (rated power) during testing with CARB fuel and synthetic 15W50 Oil. This was a change in performance compared to the initial performance test (Appendix D). The loss in torque occurred throughout the three-day testing with CARB fuel and synthetic 15W50 then leveled off. While testing with ADMM15 fuel and synthetic 15W50 oil, the final torque was unchanged compared to testing with the previous fuel/oil combination.

This change in torque is not well-understood, but the increase in wear debris in the engine oil during these sequences, and the subsequent turbocharger failure may point to a deteriorating component.

6.0 OIL IMPACT ON EMISSIONS

Graphs of the 95% Tukey confidence intervals illustrating the effects of fuel type and oil type on emissions are provided in Appendix B, while Appendix A contains statistical presentations of these results. Appendix C is a tabulation of the least squares means computed by oil and fuel across the various testing modes.

The data set is substantial, and to provide the reader an overview, portions of the data were replotted with all modes on one chart within this section. For verification of statistical significance of the fuel, oil, and combined fuel and oil effects, the reader should refer to Appendices A-C.

6.1 Oil Impact On Total Particulate

In Figure 17, the total particulate is plotted versus the engine operating modes for the three lubricants. The operating modes include steady-state modes (M20, M10, M5, M17, and M14) and one FTP Heavy-Duty transient. By weighting these steady-state modes evenly (20% each), the total particulate has been calculated for a "linear-weighted, steady-state mode."

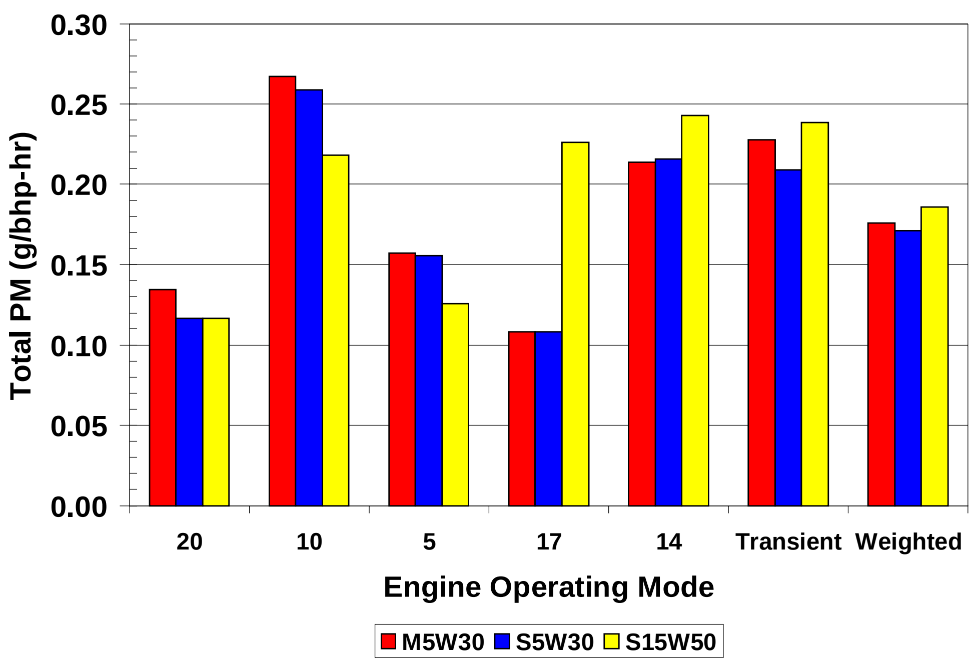

Figure 17. PM versus Mode for the Different Lubricants

Looking at Figure 17, the oil effect is unclear. The statistical interpretation (Table 8, which is copied from Appendix A) provides some insight into these data. Interestingly, for Modes 10 and 5, which are both part load conditions, the particulate emissions of the mineral 5W30 and synthetic 5W30 oils are identical, with both oils causing a significantly higher particulate emission than the synthetic 15W50 oil. On the other hand, for Mode 17, the particulate emissions of the mineral 5W30 and synthetic 5W30 oils are still statistically identical, with both oils causing a significantly lower particulate emission than the synthetic 15W50 oil. From this data above, the impacts of the lubricant changes were not clear; it was also unclear how much of the variations with the S15W50 was due to engine changes rather than the lubricant.

In most cases, the interaction between fuel and oil effects was not significant; however, there were some exceptions. Total PM at Mode 10 showed a significant interaction (Table 9).

Table 8. Statistical Analysis Results for PM: P-Values and Multiple Comparison Tests

Operating Condition	Oil
Mode 20	p=0.0658
Mode 10	p=0.0058 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50
Mode 5	p=0.0001 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50
Mode 17	p=0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50
Mode 14	p=0.0920
Transient	p=0.0016 M5W30 = S15W50 M5W30 > S5W30 S15W50 > S5W30
Weighted	p=0.1608

Table 9. Statistically Significant Fuel and Oil Interactions

Mode	Variable	P-Value	Comparison
10	Total PM	0.0043	with ADMM15 S15W50<M5W30 and S5W30
10	Non-VOF	0.0184	with S15W50 CARB > ADMM15
5	Non-VOF	0.0153	with CARB M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50
Transient	Non-VOF	0.0067	with ADMM15 M5W30=S5W30 S15W50>M5W30 S15W50>S5W30
10	NO_x	0.0314	with ADMM15 S15W50>M5W30 and S5W30
5	NO_x	0.0364	with ADMM15 S15W50>M5W30 and S5W30
Transient	CO	0.0096	with ADMM15 S15W50>S5W30 and M5W30
This represents 7 instances out of 56 conditions evaluated			

6.2 Oil Impact on Volatile and Non-Volatile Particulate

The total particulate was fractionated into the three constituents by the SwRI, direct-filter-injection, gas chromatography (DFI-GC) method.[10] As described previously, these were a fuel-derived volatile organic fraction (fuel-VOF), an oil-derived volatile organic fraction (oil-VOF), and a non-volatile organic fraction (non-VOF), which is the residual. This third component is often considered "dry soot" or the "insoluble" portion of the particulate mass. Figures 18 through 23 provide these results.

The fuel-VOF in Figure 18 should theoretically be constant among the different oils; therefore, it can be considered a check of the measurement accuracy. It is clear from this figure, considering the total particulate numbers, that the fuel-VOF is a very small portion (7-15%) of the total particulate, and except for Mode 17, there are no significant lubricant effects.

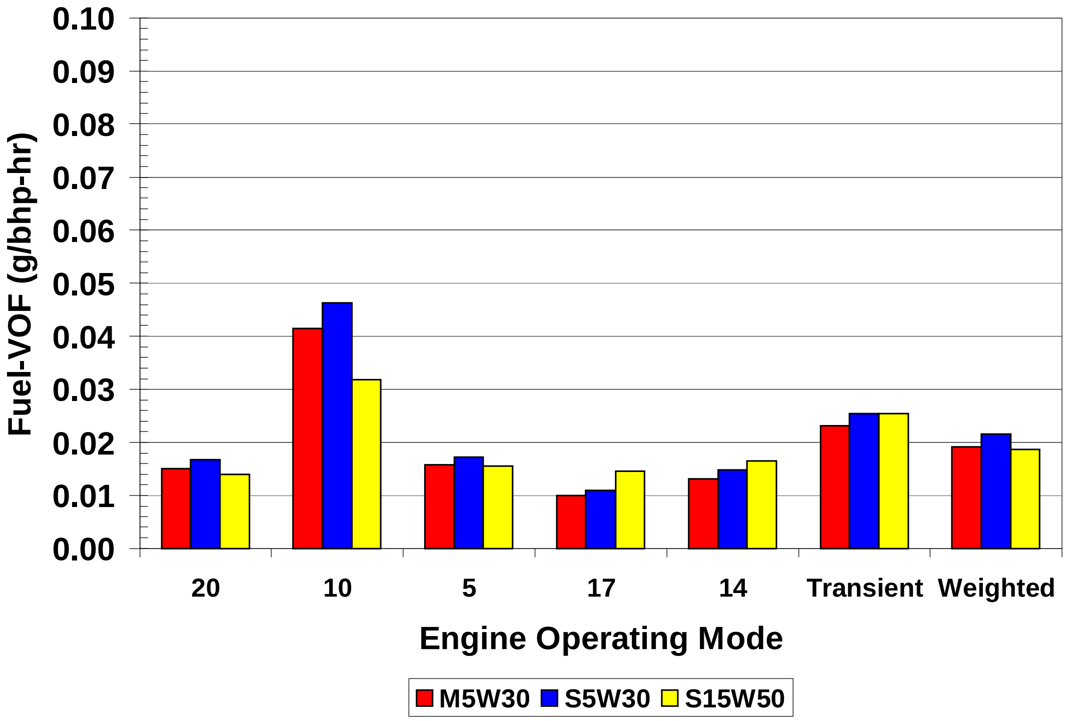

Figure 18. Fuel-VOF versus Mode for the Different Lubricants

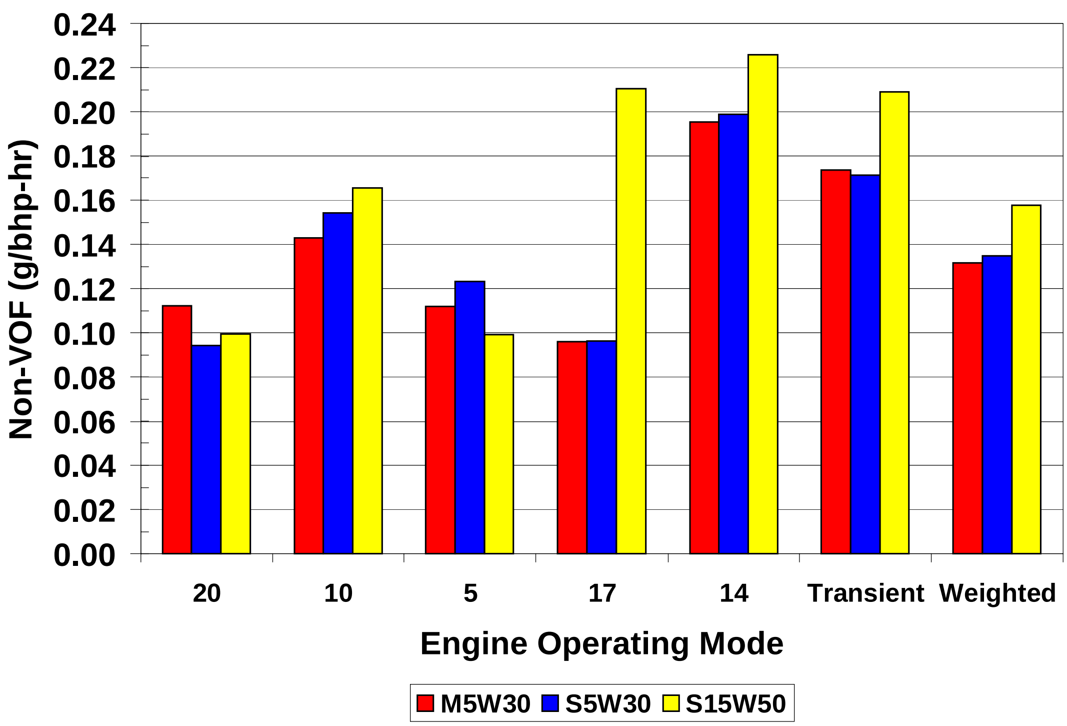

Figure 19. Non-VOF versus Mode for the Different Lubricants

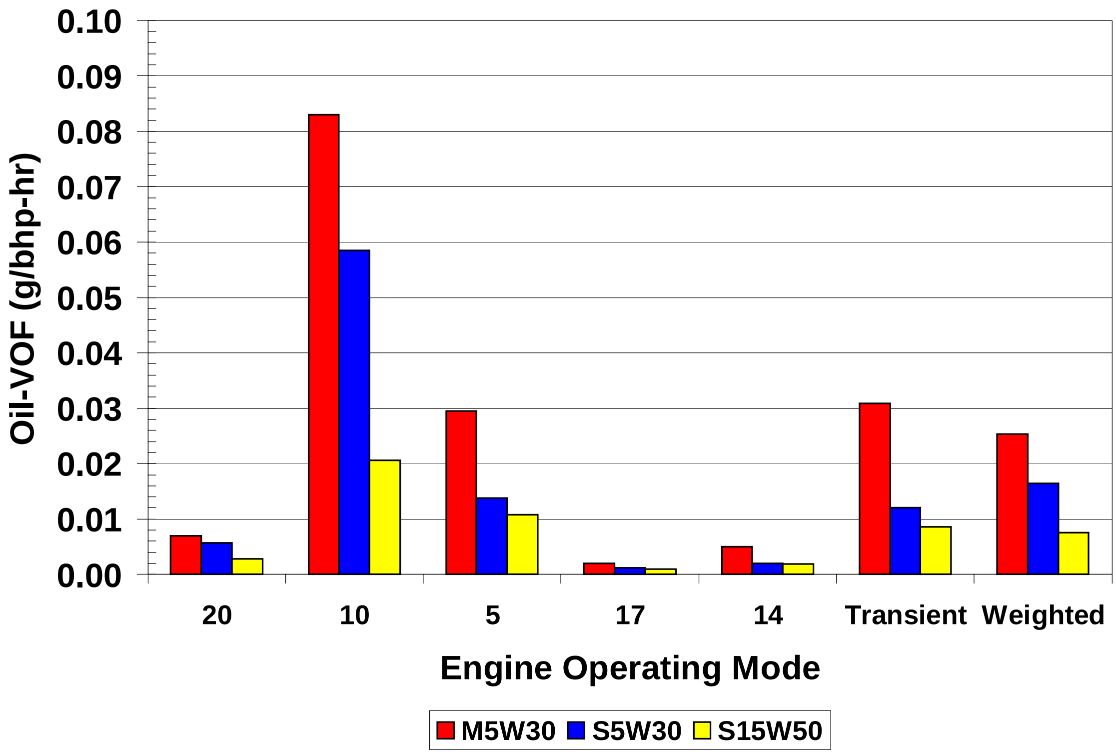

Figure 20. Oil-VOF versus Mode for the Different Lubricants

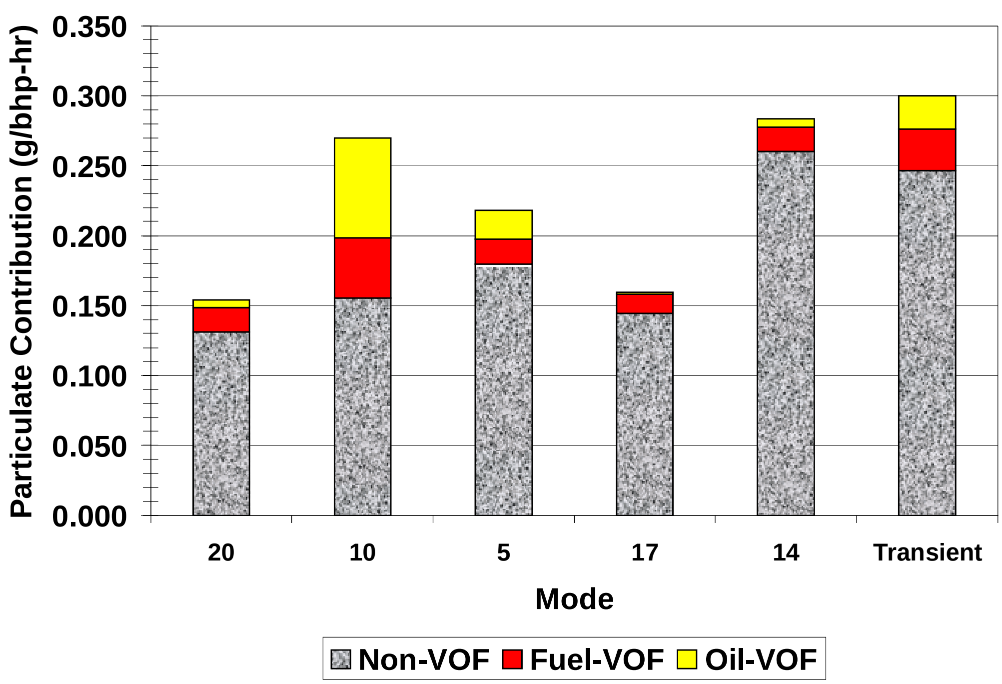

Figure 21. Fraction of Particulate into Contributors (CARB fuel and mineral 5W30 oil)

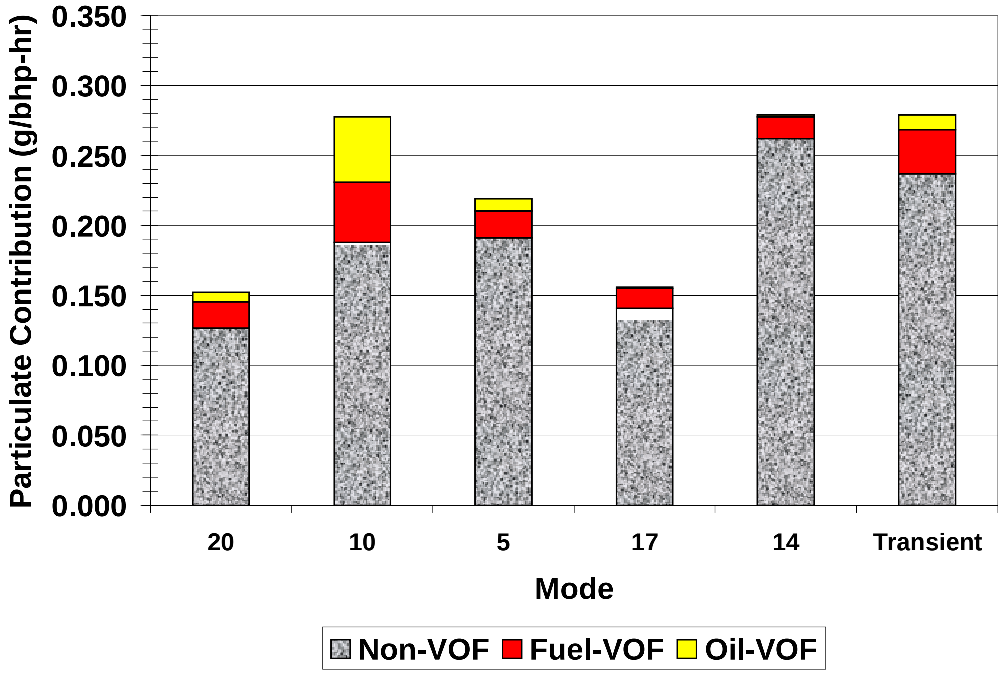

Figure 22. Fraction of Particulate into Contributors (CARB fuel and synthetic 5W30 oil)

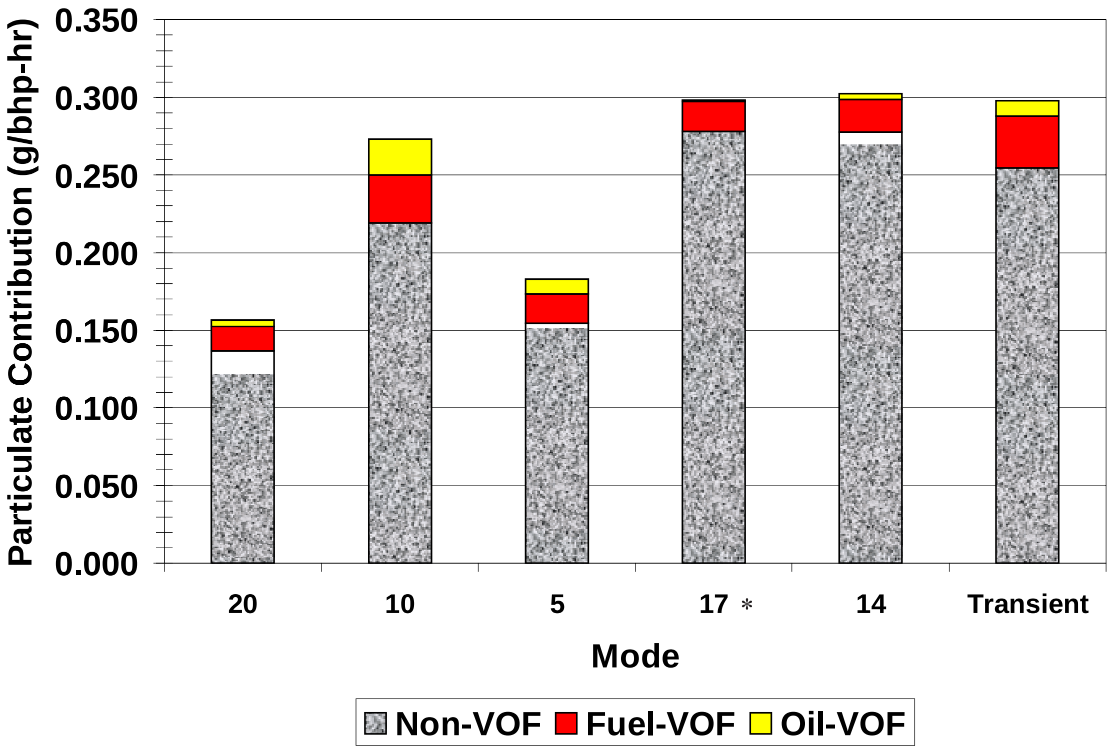

Figure 23. Fraction of Particulate into Contributors (CARB fuel and synthetic 15W50 oil).
***M17: Fuel flow increased unintentionally**

The non-VOF is by far the largest fraction of the particulate (Figure 19). Furthermore, the high-power modes (M17, M14, and transient) show increasing non-VOF during the later test on the synthetic 15W50 oil. The non-VOF is traditionally thought to be primarily fuel derived in that fuel molecules stripped of hydrogen atoms in the rich combustion zone end up as carbon skeletons, which can agglomerate and form a carbon-rich soot core with a porous surface. It is to this porous surface that incomplete-oxidized hydrocarbons, sulfates, water, and additive metals adsorb or condense. These adsorbed or condensed species can be fuel-derived (fuel-VOF) or oil-derived (oil-VOF).

If as postulated, the engine turbocharger began to degrade during the final two testing sequences where the S15W50 was being evaluated, the reduced fuel-to-air ratio at Modes 14 and 17 could lead to greater total PM and non-VOF.

Figures 20-23 illustrate the oil-VOF effects. The oil-VOF is strongly dependent on the engine operating mode and decreases strongly with increasing load. This has often been hypothesized as the result of more complete combustion of the consumed oil as a result of the higher in-cylinder and exhaust temperatures. This behavior contrasts sharply with the fuel-VOF, whose portion of the total mass was more independent of operating condition. As a consequence, the highest oil-VOF fraction is observed for Mode 10. Statistically significant differences with the change of oil were observed for Modes 10 and 5, the composite weighted steady-state mode, and for the transient mode, where the absolute change in oil-VOF is highest. No differences occurred with the change of oil at Modes 20, 17, and 14, where the oil-VOF absolute change is less than 5% of the total particulate.

An observation is that for both the weighted composite mode and the transient mode, changes in oil-VOF were found to be of the same general magnitude. This may indicate that further testing can be simplified by running only steady-state tests, then building the composite average of the results.

Figures 21-23 illustrate the composite three components of the particulate by lubricant. This information is also presented in Table 10.

Table 10. Fractional Distribution of Particulate Mass by Oil, Averaged Across Fuels			
	M5W30	**S5W30**	**S15W50**
NON-VOF			
Mode 20	83.6	80.7	85.6
Mode 10	53.4	59.5	76.0
Mode 5	71.2	79.9	79.0
Mode 17	88.9	88.8	93.1
Mode 14	91.5	92.2	92.5
Weighted	74.8	78.0	85.7
Transient	76.3	82.1	86.0
FUEL-VOF			
Mode 20	11.2	14.4	12.0
Mode 10	15.5	17.9	14.6
Mode 5	10.1	11.1	12.4
Mode 17	9.3	10.1	6.5
Mode 14	6.1	6.9	6.8
Weighted	10.8	12.5	10.2
Transient	10.1	12.2	10.4
OIL-VOF			
Mode 20	5.2	4.9	2.4
Mode 10	31.1	22.6	9.4
Mode 5	18.8	8.9	8.6
Mode 17	1.9	1.1	0.4
Mode 14	2.3	0.9	0.8
Weighted	14.4	9.5	4.1
Transient	13.6	5.8	3.5

6.3 Oil Impact on CO

The oil effect on CO is shown in Figure 24. The effect is very weak, and for most conditions there is no statistically significant change. The increase in CO for Mode 17 by changing to S15W50 oil is due to a change in the local in-cylinder air/fuel ratio. The change in Mode 10 is believed to be an anomalous measurement.

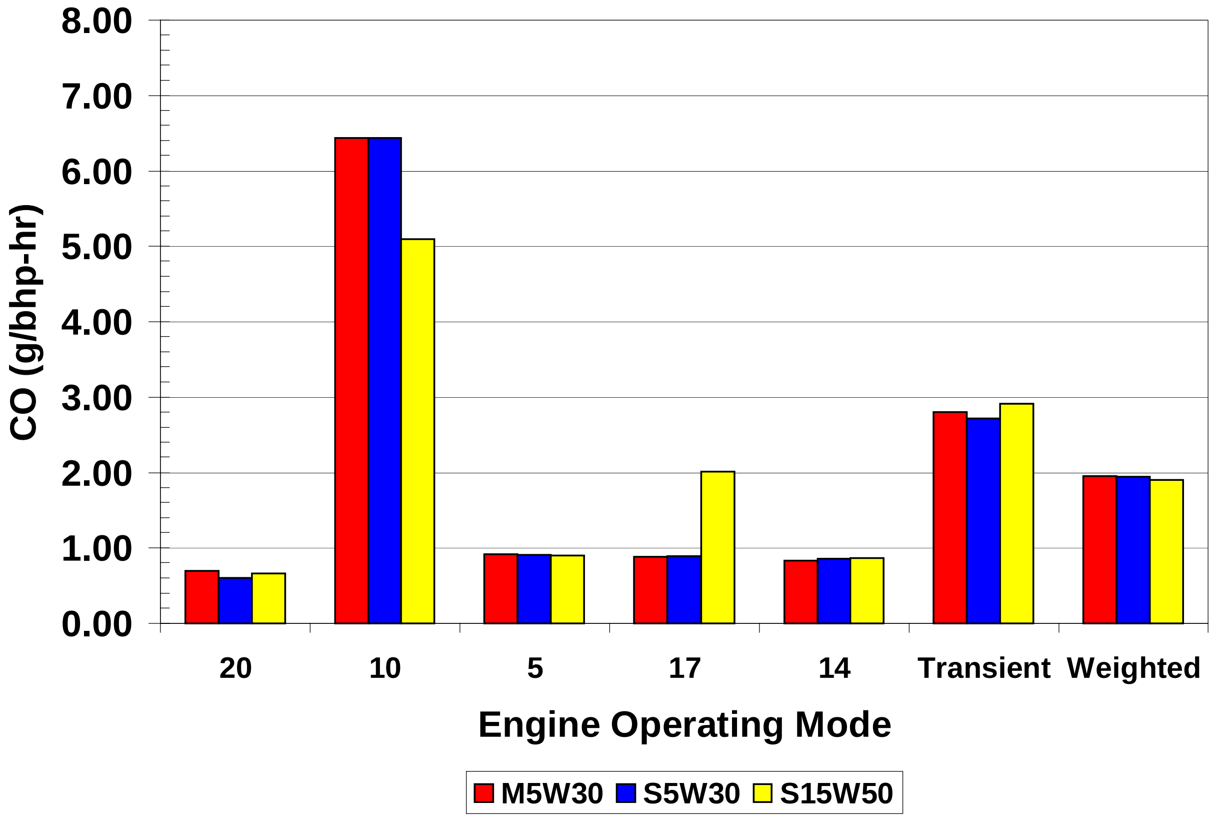

Figure 24. Oil Impact on CO

6.4 Oil Impact on NOx

The oil effect on NO_x is shown in Figure 25. It is statistically significant for all conditions. In all modes except Mode 17, the NO_x increases with the change to the presumedly higher-friction S15W50 oil. At first this is quite surprising, but it can be explained rather simply. Since the engine is operated at constant brake mean effective pressure (BMEP), a higher-friction lubricant that results in a higher friction mean effective pressure (FMEP) will have to be offset by a higher indicated mean effective pressure (IMEP), because the following equation is valid at all times:

$$BMEP = IMEP - FMEP$$

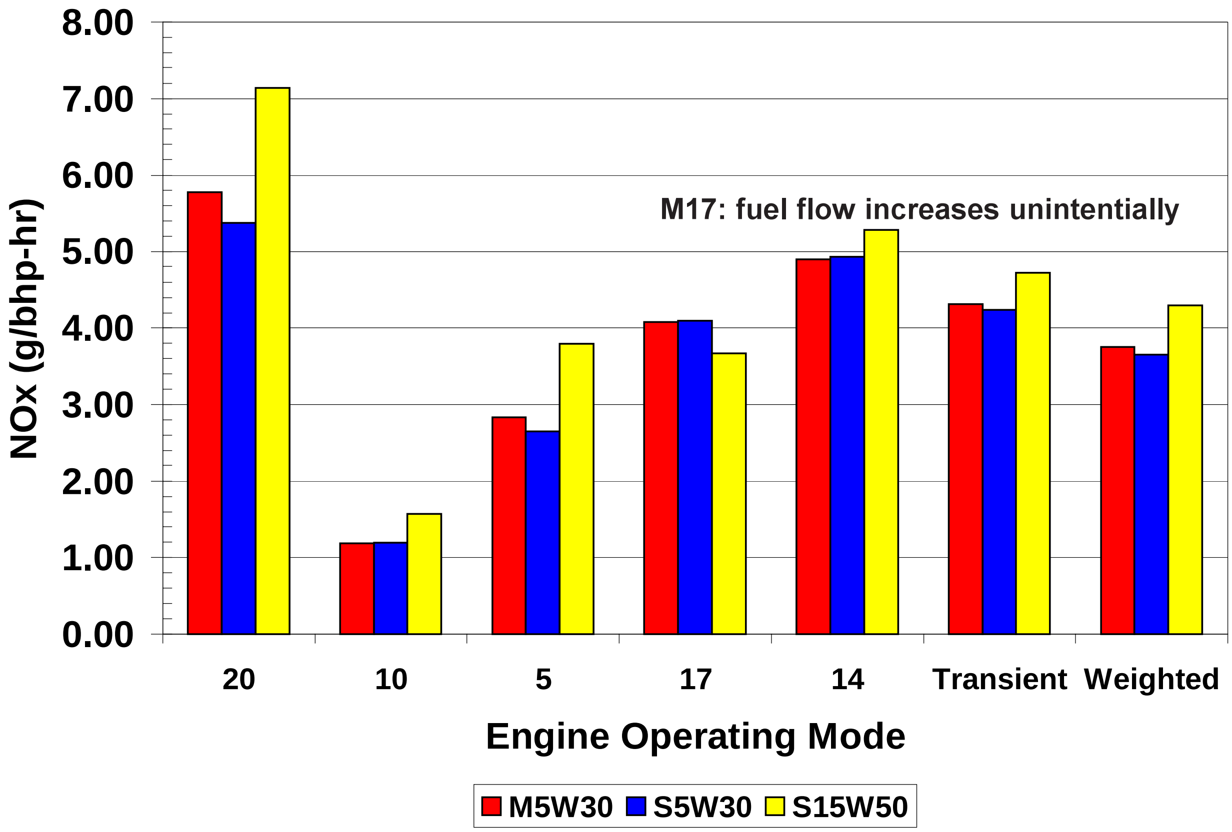

Figure 25. Oil Impact on NOx

At idle, FMEP equals IMEP, becoming an increasingly smaller fraction as torque output increases. Thus, increasing friction due to a lubricant change will have the greatest impact at low-load conditions, which is indeed generally the case. The NO_x increase is 33% at Mode 10 (2000 rpm, 25 ft-lb), 34% at Mode 5 (2600 rpm, 111 ft-lb), and 31% at Mode 20 (1,000 rpm, 75 ft-lb).

The magnitude of this increase in NO_x emissions with a higher-friction oil is rather surprising.

The data suggest that the mineral 5W30 and the synthetic 5W30 oils have a similar effective in-situ friction, with the friction of the synthetic 5W30 slightly lower than the one for the mineral 5W30 oil.

6.5 Oil Impact on CO_2

The oil effect on CO_2 is shown in Figure 26. The CO_2 emissions increase significantly when the oil is changed to the high-viscosity synthetic 15W50 oil. This supports the friction effect postulated in the NO_x results in Figure 25. The increase in CO_2 and fuel consumption when changing from the mineral 5W30 or synthetic 5W30 oils to the high-viscosity synthetic 15W50 oils ranges from 2.0% (Mode 20) to 11.6% (Mode 17). However, the degree of change with engine load is surprising in that the highest increase is at full-load condition, where FMEP as a fraction of the IMEP is expected to be lowest. The increase in CO_2 is approximately 8% for the composite weighted steady-state mode and 12% for the transient mode.

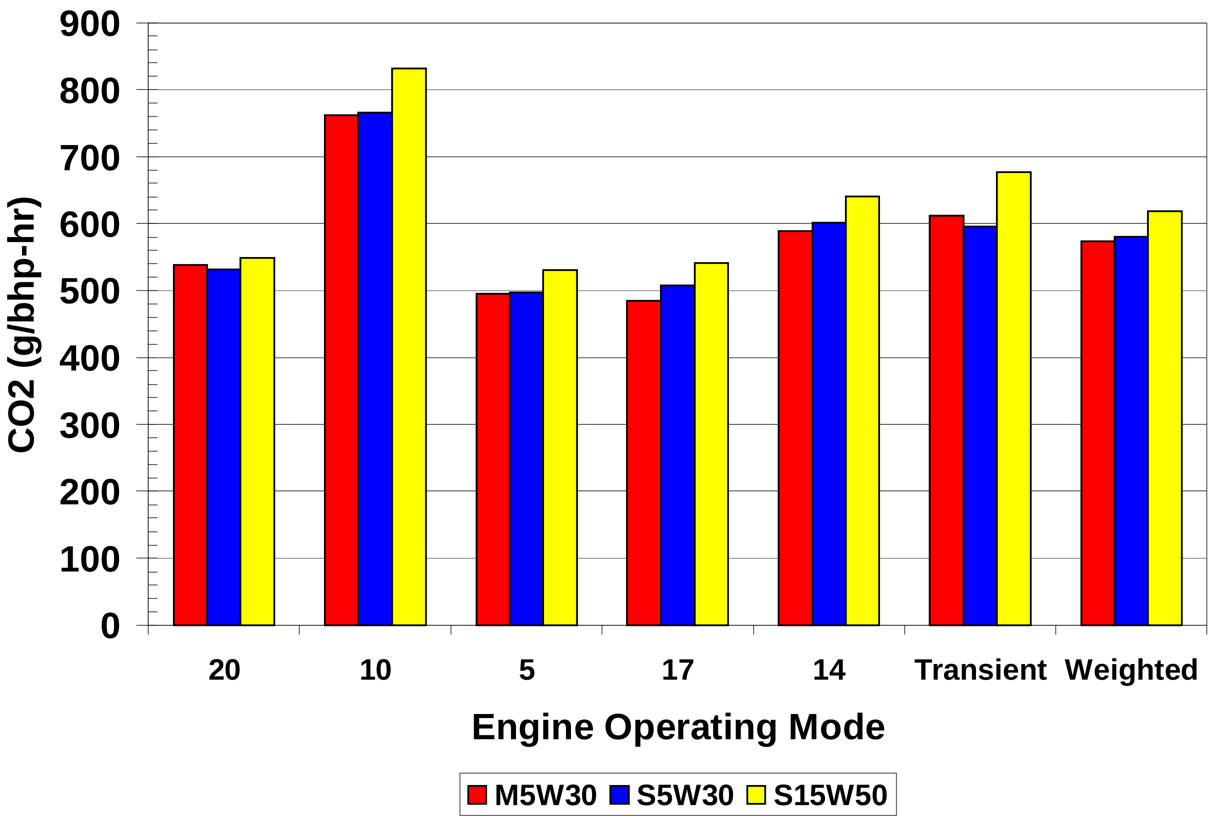

Figure 26. Oil Impact on CO_2

6.6 Oil Impact on HC

The oil effect on HC is quite strong and trends in the same direction regardless of the operating condition (Figure 27). Since the HC are both fuel and oil derived, it is tempting to compare Figures 27 and 20. However, since the collection efficiency of the HC for the filters applied in this study is unknown, it is not possible to further quantify the oil contribution to the HC emissions.

The significant reductions in HC for synthetic 15W50 are shown at the following operating modes:

- Mode 10 is 34%
- Mode 17 is 100%
- Mode 14 is 65%

Substantial reductions in HC can thus be obtained by changing lubricants, although the HC for a CIDI engine are at low absolute levels.

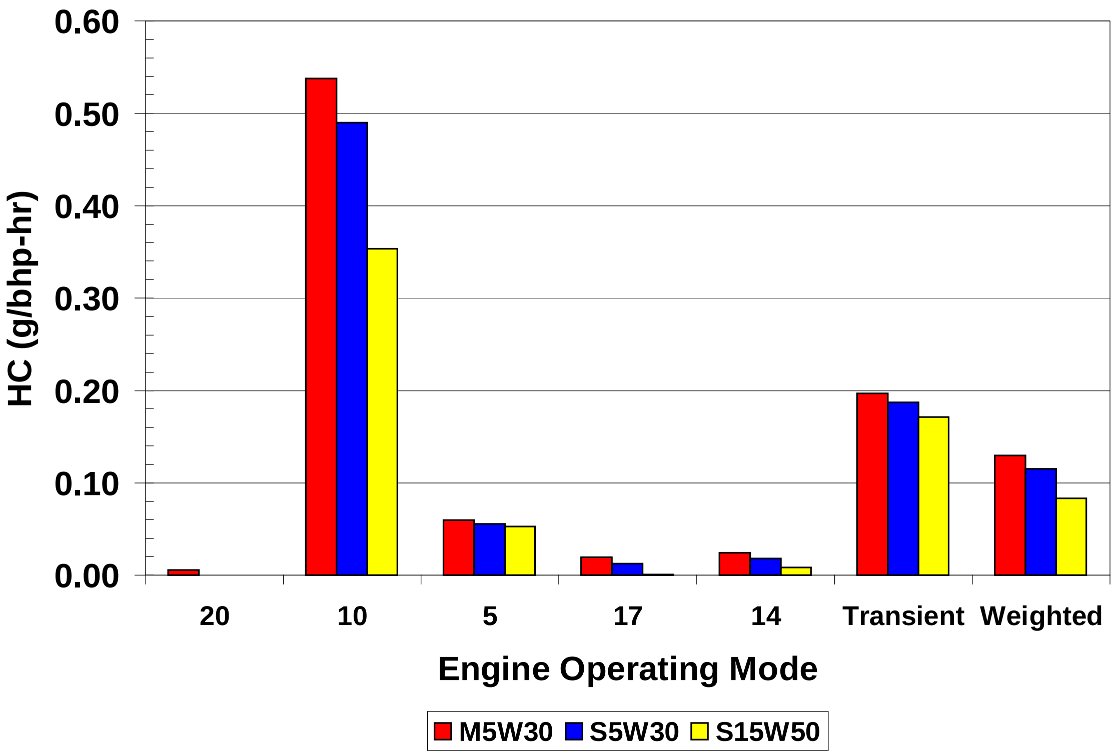

Figure 27. Oil Effect on HC

6.7 Oil Consumption

Oil additive metals in the particulate were measured in an attempt to obtain a rough measure of engine oil consumption. The technical approach applied is based on findings in a SwRI Internal Research Project.[24] This technique is fraught with problems, since oil consumed through evaporation will not contribute additive metals to the PM. There is also no assurance that additive metals are consumed in proportion to the total oil consumption nor knowledge of the additive metal collection efficiency by the PM filter. However, the data are available at little additional cost, and the resulting information may be helpful in interpreting the project results.

47-mm Nucleopore filters were applied since they have virtually no metal concentration in the media substrate, providing a low background level of metals. While multiple 47-mm filters were collected in parallel, only one 47-mm filter was analyzed. The metals were removed from the filters by a concentrated nitric acid wash, and the resulting liquid analyzed by coupled plasma emission spectroscopy. The method is described in greater detail in Appendix F. Table 11 provides the results of the determinations.

While many conditions yielded additive metal levels too low to be detected, the results are somewhat surprising in that calcium is detected in significant concentrations at most conditions, while phosporus and zinc appear to be in much lower concentrations despite the fact that the three metals were present in the new oil in approximately equal concentrations. This is particularly surprising when considering the analytical method detection limits, which should have been able to detect zinc at 0.5 µg per filter, compared to the 5 µg per filter detection limit of calcium.

Table 11. Results of Coupled Plasma Emission Spectroscopy						
Oil	**Condition**	**Ba**	**Ca**	**Mg**	**P**	**Zn**
Mineral 5w30	M20		5.28%			0.25%
Mineral 5w30	M10		6.38%			0.23%
Mineral 5w30	M5		6.57%	1.24%		
Mineral 5w30	M17		3.71%		2.84%	
Mineral 5w30	M14		1.60%			0.06%
Mineral 5w30	Transient	0.42%	4.88%			
Synth 5w30	M20		5.46%			
Synth 5w30	M10		4.31%			
Synth 5w30	M5		2.83%			
Synth 5w30	M17		3.89%			0.09%
Synth 5w30	M14		2.33%			0.11%
Synth 5w30	Transient		6.30%			0.45%
Synth 15w50	M20		2.49%			0.70%
Synth 15w50	M10					
Synth 15w50	M5		4.45%			0.44%
Synth 15w50	M17					
Synth 15w50	M14		0.78%			0.11%
Synth 15w50	Transient					

7.0 FUEL IMPACT ON EMISSIONS

7.1 Fuel Impact on Particulate

An underlying question that led to this project was concern that as diesel fuel reformulation reduces fuel-derived particulate emissions, the engine lubricant would at some point become a significant source of particulate. CARB was selected as a reasonable representation of a typical California diesel fuel, and for these purposes also adequately represents a future reformulated United States 49-state diesel fuel. ADMM15 is an oxygen-containing experimental diesel fuel formulation that has been shown in other research [2] to substantially reduce engine-out particulate emissions.

As expected, there was a statistically significant difference in particulate emissions between the two fuels, which is readily apparent in the total particulate mass (Figure 28). There is no direct correlation between engine operating mode and the fuel impact on particulate.

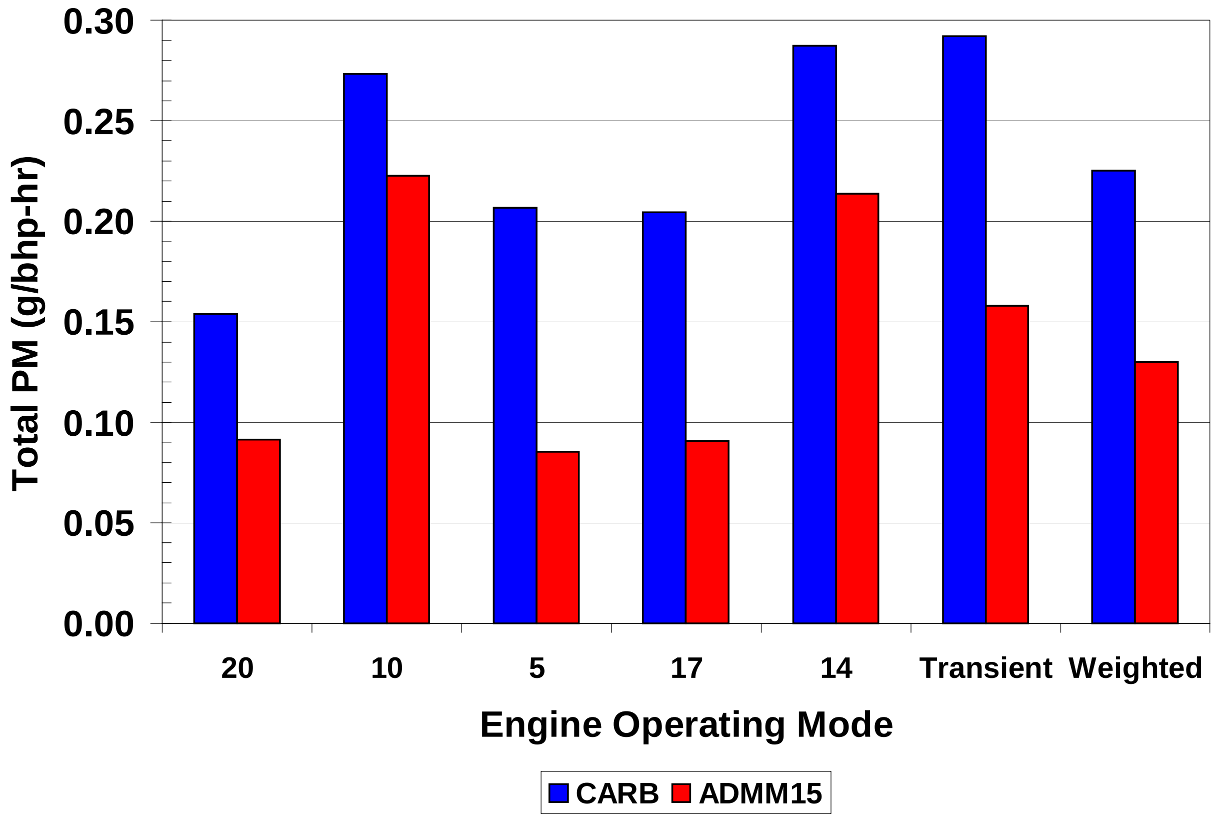

Figure 28. PM versus Mode for the Different Fuels

Figure 29 plots the fuel-VOF as a function of fuel, averaged over the three oils. The decrease with ADMM15 is statistically significant for most modes: Modes 5, 17, 14, transient and composite. However, the absolute magnitude of the changes is small. Clearly, the fuel change has a stronger relationship to fuel-VOF differences than the lubricant changes, as one would hope. Likewise, as shown in Figure 30, there is little fuel impact on oil-VOF. In this case, only the change in Mode 5 and the steady-state composite are statistically significant. When looking at this figure, it is tempting to postulate that the oil-VOF is increased with ADMM15. However, as noted earlier, none of these differences are statistically significant.

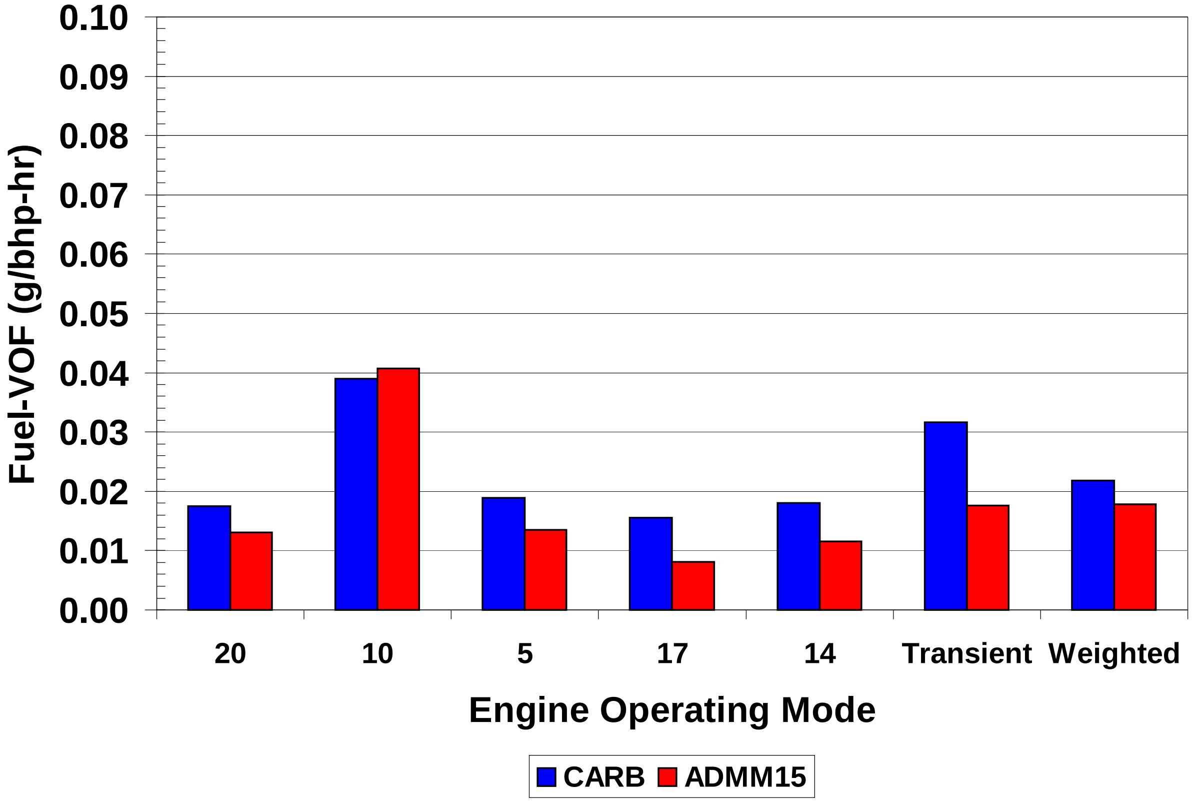

Figure 29. Fuel-VOF versus Mode for the Different Fuels.

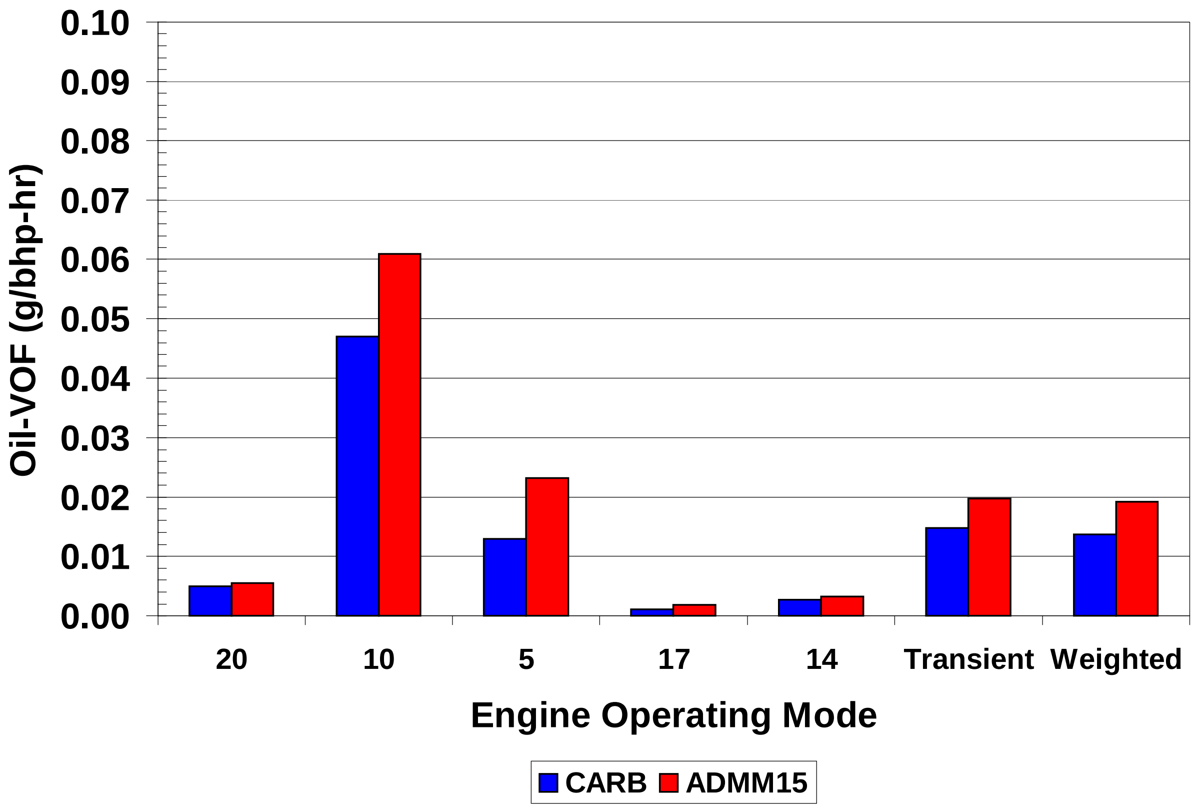

Figure 30. Oil-VOF versus Mode of the Different Fuels.

As seen in Figure 31, the particulate reduction produced by ADMM15 is largely due to a decrease in the mass of the non-volatile portion of the particulate. At all modes, the difference in non-volatile particulate is large and statistically significant. While these results support the conventional thinking that the non-VOF fraction is predominantly fuel derived, the fuel-by-lubricant interaction had a statistically significant impact on non-VOF at three modes (10, 5 and transient). As alluded to earlier in the discussion of estimating oil consumption, the lubricant additive metals alone can make up a substantial portion of the non-VOF. At the current time, there is no widely accepted technique for evaluating the lubricant base stock contribution to non-VOF.

The particulate has been fractionated in Figures 32-34, and the data are presented in tabular form in Table 12. It is interesting that when the absolute particulate emission decreases by applying a less particulate-contributing fuel such as ADMM15, the oil-VOF simply scales up since the oil-VOF is independent of fuel-VOF, which is supported by the interaction plots in Appendix B.

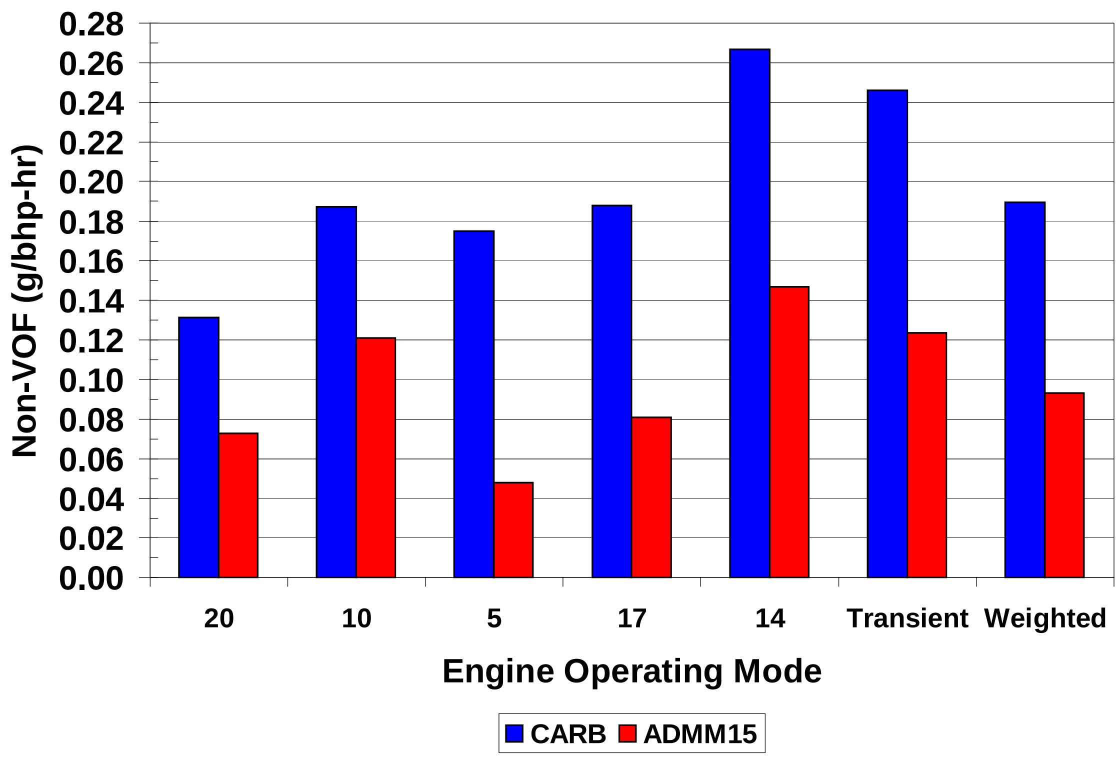

Figure 31. Non-VOF versus Mode for the Different Fuels

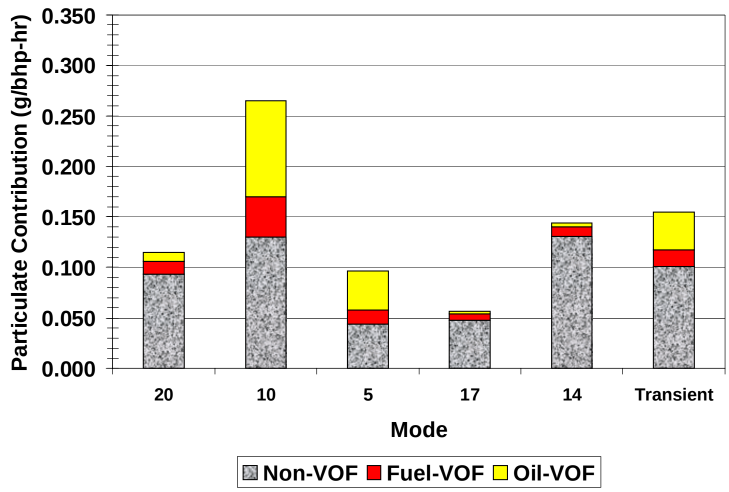

Figure 32. Fraction of Particulate into Contributors (ADMM15 fuel and mineral 5W30 oil)

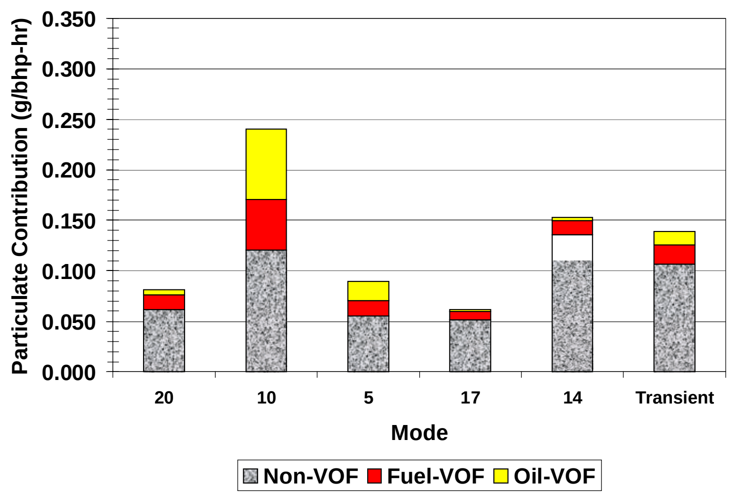

Figure 33. Fraction of Particulate into Contributors (ADMM15 fuel and synthetic 5W30 oil)

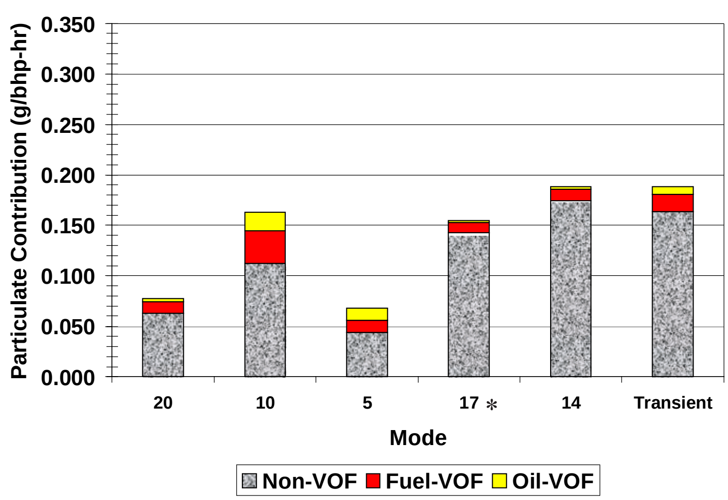

Figure 34. Fraction of Particulate into Contributors (ADMM15 fuel and synthetic 15W50 oil)
***M17: Fuel Flow increased unintentionally, refer to Figure 23.**

Table 12. Fraction Data of Particulate by Fuel. Average Across Lubricants		
	CARB	ADMM15
NON-VOF		
Mode 20	85.4	79.6
Mode 10	68.5	54.3
Mode 5	84.6	56.6
Mode 17	91.8	89.1
Mode 14	92.8	90.8
Weighted	84.2	71.6
Transient	84.2	76.8
FUEL-VOF		
Mode 20	11.4	14.3
Mode 10	14.3	18.3
Mode 5	9.1	16.0
Mode 17	7.6	8.9
Mode 14	6.3	7.2
Weighted	9.7	13.7
Transient	10.8	10.9
OIL-VOF		
Mode 20	3.2	6.0
Mode 10	17.2	27.4
Mode 5	6.2	27.4
Mode 17	0.5	2.0
Mode 14	0.9	2.0
Weighted	6.1	14.7
Transient	5.0	12.3

7.2 Fuel Impact on NOx

The fuel impact on NO_x is shown in Figure 35. For most conditions, ADMM15 increases the NO_x emissions compared to CARB fuel. The increase is 12% for the composite weighted steady-state mode, and 6% for the transient mode.

7.3 Fuel Impact on HC

The impact of fuel on HC emissions is shown in Figure 36. For the composite weighted steady-state mode and for the transient mode, the decrease from CARB to ADMM15 fuel is 33%. The highest absolute HC emissions are seen at light load, such as Mode 10, which amounts to 0.57 g/bhp-hr. Here, the decrease in HC by switching fuel from CARB to ADMM15 is as much as 37%. There is no fuel effect at the other steady-state modes.

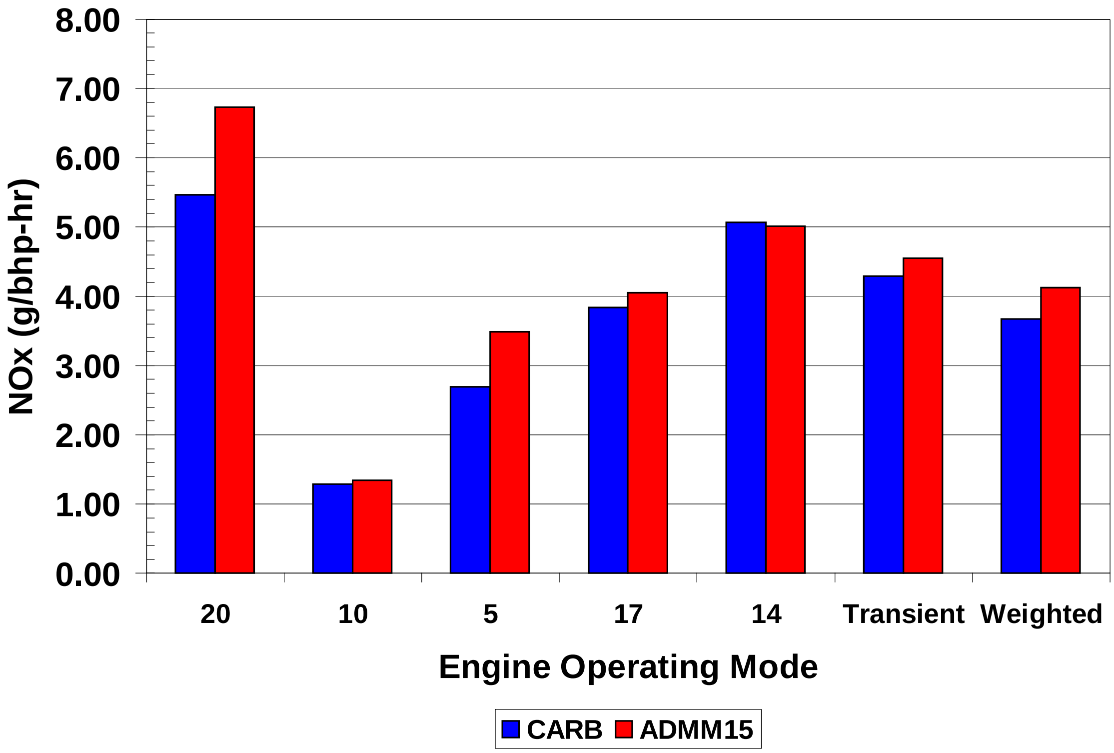

Figure 35. Fuel Effect on NOx

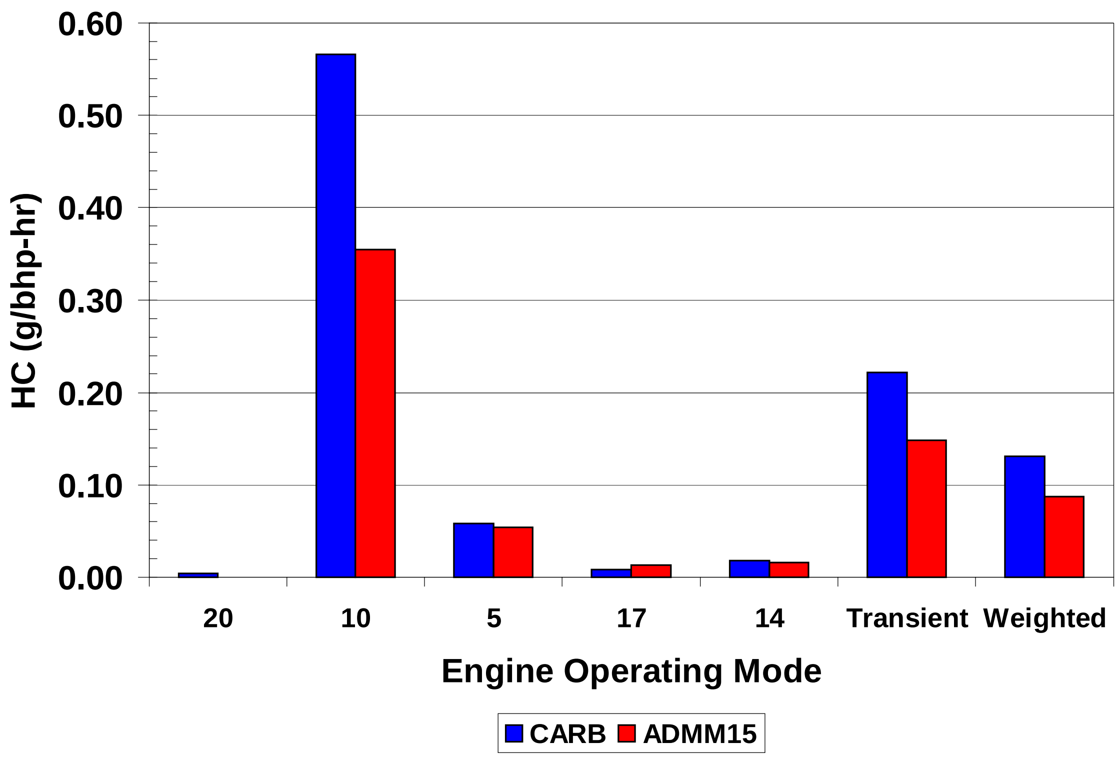

Figure 36. Fuel Effect on HC

7.4 Fuel Impact on CO

The fuel effect on CO is shown in Figure 37 and is stronger than the lubricant's impact on CO. For all but Mode 20, there is a statistically significant decrease with ADMM15 fuel. The reduction in CO with ADMM15 fuel is 19% for the composite-weighted, steady-state mode and 29% for the transient mode.

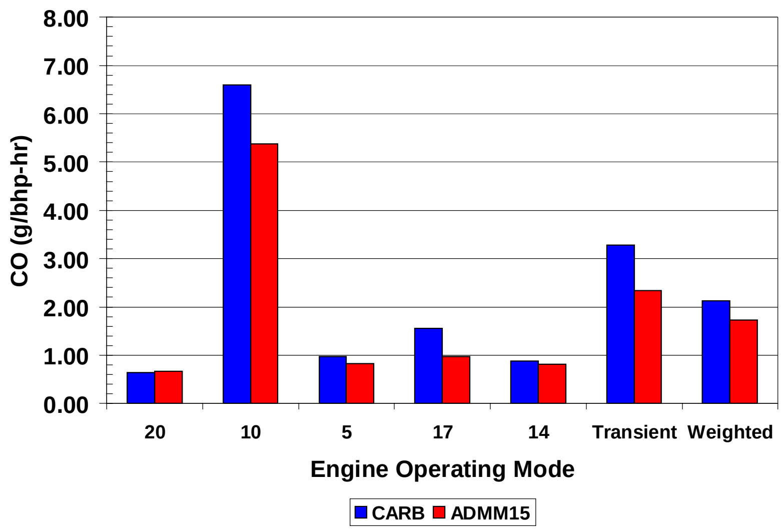

Figure 37. Fuel Effect on CO

7.5 Fuel Impact on CO_2

Other than Mode 20, there is no statistically significant change in CO_2 from changing between the two test fuels (Figure 38). Thus, one would not expect any difference in energy efficiency.

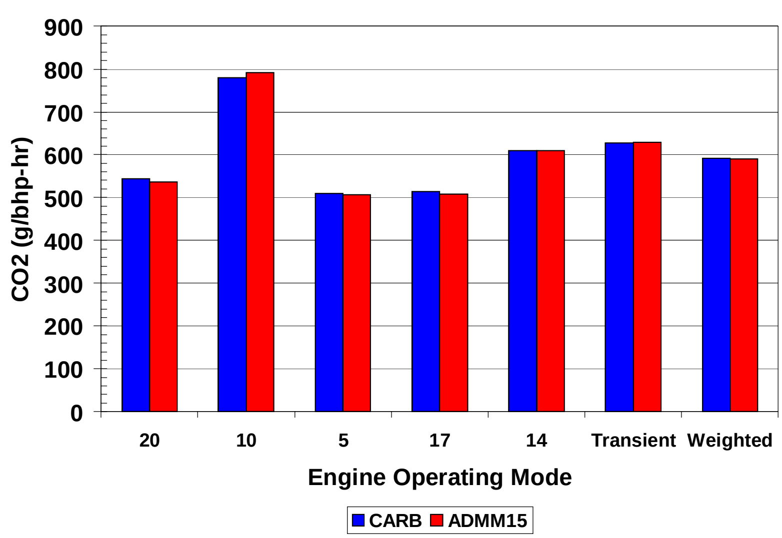

Figure 38. Fuel Effect on CO_2

8.0 CONCLUSIONS

As expected, the fuels used in this study produced significantly different engine-out exhaust emissions. Table 13 summarizes the impact that changing from CARB to ADMM15 produced at steady-state conditions. The transient results were similar. The decrease in particulate emission with ADMM15 is primarily the result of a reduction in the non-volatile portion of the particulate mass (Table 14).

Table 13. Impact of Fuel on Regulated Emissions (Average Over Oils and For Weighted Steady-State Mode)

Fuel	PM	NO_x	CO	HC
CARB	0.225	3.670	2.129	0.131
ADMM15	0.130	4.123	1.729	0.088
Percent Change	-42.2	12.3	-18.8	-32.8

Table 14. Impact of Fuel on Particulate Emissions (Average Over Oils and For Weighted Steady-State Mode)

Fuel	NON-VOF	OIL-VOF*
CARB	0.190	0.014
ADMM15	0.093	0.019
Percent Change	-51.1	35.7
* Only one of five modes making up composite was significant.		

There were several interesting trends identified in the lubricants' evaluation. Looking solely at the total particulate mass emissions:

- There was no difference between the two 5W-30 grade lubricants.
- The synthetic 15W-50 grade lubricant produced lower PM than the other lubricants at Modes 5 and 10, and the transient procedure. At Mode 17, the synthetic 15W-50 grade had higher PM than the other lubricants. Averaged over all the steady-state modes, there was no difference in PM among the three lubricants.

The major component of the particulate mass was the non-volatile portion, which was dominated by fuel effects. Test-to-test variation in the non-volatile portion of the particulate tended to dominate other effects. Thus, the lubricant effects were not as apparent until the oil-derived portion of the volatile fraction of the particulate was observed. While there was some variability in results at the various steady-state modes, their composite result showed a clear trend.

The mass of oil-VOF was different among the three lubricants, with the ranking from highest level to lowest being mineral 5W30, synthetic 5W30, then synthetic 15W50. With the CARB fuel, the oil-VOF was reduced from 27 percent of the PM with the mineral 5W30 oil to 8 percent with synthetic 15W50 for the important steady-state Mode 10.

The composite oil-VOF result tends to correlate with the lubricant Noack volatility number, illustrated in Figure 39, and with kinematic viscosity at 100°C. While it is tempting to draw conclusions about lubricant properties related to PM contribution, with only three lubricant samples and an engine-related problem clouding the synthetic 15W50 results, such speculation seems premature.

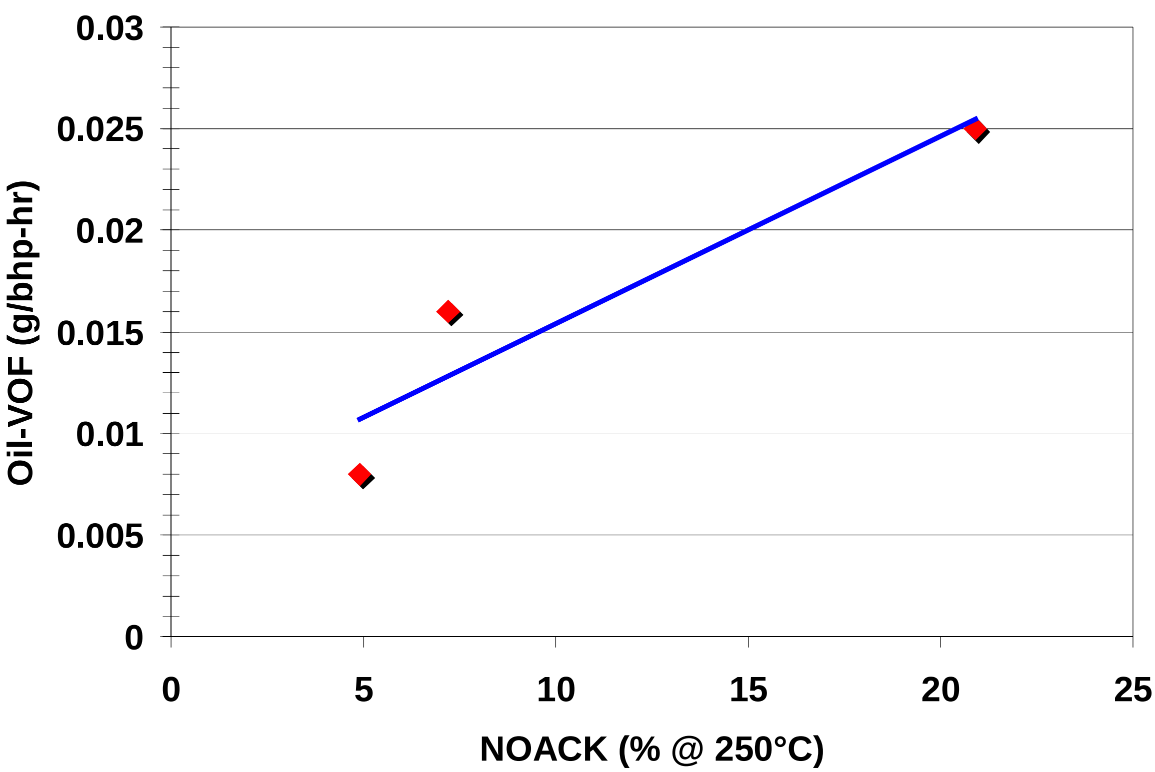

Figure 39. Non-VOF versus Noack

The non-volatile particulate deserves additional consideration. While the fuel had the strongest relationship with changes in non-VOF, there were statistically significant lubricant effects at three modes (5, 17, transient) and the composite. Furthermore, there were three modes (10, 5, and transient) at which there was an identified fuel/lubricant interaction. In all these cases save one, the mineral and synthetic 5W30 products behaved identically, while there was a difference with the synthetic 15W50. Part of this lubricant effect is the contribution that the additive metals (or more likely the additive metal oxides) make to the non-volatile portion of the particulate.

The choice of lubricant has a statistically significant effect on engine-out NO_x emissions. The synthetic 15W50 lubricant increased engine-out NO_x emissions by 10 to 20 percent compared to the other two lubricants. There was also a significant increase in CO_2 emission for the average steady-state condition, with a 5 to 10 percent increase with the synthetic 15W50. Both of these effects are apparently due to increased friction.

As fuel-derived particulate emissions are reduced through fuel reformulation, as in this study, or fuel injection and combustion improvements, the data developed here indicate that the lubricant will become a larger fraction of the total particulate mass. Looking at the composite data, with the mineral 5W-30 lubricant and CARB fuel, the oil fraction of the particulate is about 9.6 percent of the total. With the ADMM15 fuel, the oil contribution to the reduced total mass of particulate now is 22%. This does not consider any contribution by the lubricant to the non-volatile portion of the particulate. An absolute reduction of fuel-VOF and non-VOF, and thus total particulate, will result in an increase in the oil-VOF fraction (%). This is basically a dilution effect.

This argument is interesting, since the fuel-derived particulate will be decreased for CIDI engines over the next few years, and as a consequence, assuming that the lubricant-derived particulate remains unchanged, the lubricant-derived particulate as a fraction will increase.

9.0 RECOMMENDATIONS

Based on the findings of this preliminary study, there are several issues that SwRI believes warrants further investigation.

- Since the heavy-duty transient procedure used in this work is intended for heavy-duty engine applications and the DaimlerChrysler engine is intended for light duty applications, verification of these results using a full vehicle chassis dynamometer transient test procedure should be conducted. Such testing would also provide information on whether the synthetic 15W50 results were influenced by the subsequent turbocharger failure.
- In the continuing effort to reduce engine friction, the engine industry is considering lower viscosity lubricants than the 5W30 grade products evaluated here. Use of a 0W20 grade lubricant should be considered as an element in any future work.
- These results suggest that lubricant physical and chemical characteristics such as Noack volatility or kinematic viscosity can affect the contribution the lubricant makes to particulate and NO_x emissions. The relationship between lubricant characteristics and engine emissions needs to be studied in a designed set of experiments to identify the controlling lubricant physical and chemical properties. Such a study should be conducted with more than one engine design.

A method for quantifying the total contribution made by the lubricant to the non-volatile portion of the particulate is needed. The use of additive metals as a tracer, which was used in this study, has obvious limitations. Tags or tracers, which could be incorporated uniformly into the lubricant base stock, should be investigated.

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APPENDIX A
ANOVA Statistical Results

Statistical Significance of Results
Particulate (PM)

Conclusions:

- The CARB fuel produced a significantly higher average PM than the ADMM15 fuel at all 7 engine operating conditions.
- Statistically significant differences were found between the three oils at four engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average PM levels that were similar but higher than the Synthetic 15W50 at modes 10, 5, and transient conditions. At mode 17, Mineral 5W30 and Synthetic 5W30 produced similar but significantly lower average PM than the Synthetic 15W50.
- The interaction at mode 10 was significant. In this case at the ADMM15 fuel, the Synthetic 15W50 fuel produced significantly lower average PM levels that either the Mineral 5W30 or the Synthetic 5W30. The Mineral 5W30 and Synthetic 5W30 were not significantly different at the ADMM15 fuel.

Table A-1. Statistical Analysis Results. P-values and Multiple Comparison Tests.

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.0001 CARB>ADMM15	0.0658	0.0643
Mode 10	0.0003 CARB>ADMM15	0.0058 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.0043 At ADMM15, S15W50 < M5W30 and S5W30
Mode 5	0.0001 CARB>ADMM15	0.0001 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.3251
Mode 17	0.0001 CARB>ADMM15	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.4849
Mode 14	0.0001 CARB>ADMM15	0.0920	0.6534
Transient	0.0001 CARB>ADMM15	0.0016 M5W30 = S15W50 M5W30 > S5W30 S15W50 > S5W30	0.1062
Weighted	0.0001 CARB>ADMM15	0.1608	0.1169

Statistical Significance of Results
Fuel-VOF

Conclusions:

- The CARB fuel produced a significantly higher average Fuel-VOF than the ADMM15 fuel at modes 5, 17, 14, and transient operating conditions.
- Statistically significant differences were found between the three oils at mode 17. Synthetic 15W50 produced average Fuel-VOF levels that were significantly higher than the Mineral 5W30.
- No significant interactions were found at any of the operating conditions.

Table A-2. Statistical Analysis Results. P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.0933	0.6920	0.9923
Mode 10	0.8204	0.2933	0.8465
Mode 5	0.0394 CARB>ADMM15	0.8501	0.8615
Mode 17	0.0001 CARB>ADMM15	0.0178 S15W50 > M5W30	0.5678
Mode 14	0.0001 CARB>ADMM15	0.4452	0.2803
Transient	0.0103 CARB>ADMM15	0.8835	0.9606
Weighted	0.0714	0.5039	0.6437

Statistical Significance of Results
Oil-VOF

Conclusions:

- The ADMM15 fuel produced a significantly higher average Oil-VOF than the CARB fuel at mode 5 and the weighted conditions.
- Statistically significant differences were found between the three oils at four engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average Oil-VOF levels that were similar but higher than the Synthetic 15W50 at modes 10, 5, transient conditions. At the weighted condition, all three oils were significantly different. Mineral 5W30 produced significantly higher average Oil-VOF than the Synthetic 5W30, which produced significantly higher average Oil-VOF than the Synthetic 15W50.
- No significant interactions were found at any of the operating conditions.

Table A-3. Statistical Analysis Results: P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.7816	0.1920	0.4253
Mode 10	0.2116	0.0008 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.5003
Mode 5	0.0048 ADMM15>CARB	0.0002 S5W30 = S15W50 M5W30 > S5W30 M5W30 > S15W50	0.1268
Mode 17	0.2477	0.3468	0.5198
Mode 14	0.8693	0.5422	0.8197
Transient	0.2392	0.0006 S5W30 = S15W50 M5W30 > S5W30 M5W30 > S15W50	0.2689
Weighted	0.0312 ADMM15>CARB	0.0001 M5W30 > S5W30 > S15W50	0.2973

Statistical Significance of Results
Non-VOF

Conclusions:

- The CARB fuel produced a significantly higher average Non-VOF than the ADMM15 fuel at all 7 engine operating conditions.
- Statistically significant differences were found between the three oils at four engine operating conditions. At mode 5, Synthetic 5W30 produced average Non-VOF levels that were significantly higher than the Mineral 5W30, which in turn produced average Non-VOF levels significantly higher than Synthetic 15W50. At mode 17, transient and weighted operating conditions, Mineral 5W30 and Synthetic 5W30 produced similar but significantly lower average Non-VOF than the Synthetic 15W50.
- Interactions at modes 10, 5, and transient were significant. For mode 10 at the Synthetic 15W50 oil, the CARB fuel produced significantly higher average Non-VOF than the ADMM15 Fuel. For mode 5 using the CARB fuel, Mineral 5W30 and Synthetic 5W30 produced average Non-VOF levels that were similar but higher than the Synthetic 15W50. For the transient operating condition using the ADMM15 fuel, Mineral 5W30 and Synthetic 5W30 produced average Non-VOF levels that were similar but lower than the Synthetic 15W50.

Table A-4. Statistical Analysis Results: P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.0001 CARB>ADMM15	0.1526	0.1467
Mode 10	0.0001 CARB>ADMM15	0.2300	0.0184 At S15W50, CARB > ADMM15
Mode 5	0.0001 CARB>ADMM15	0.0004 S5W30 > M5W30 > S15W50	0.0153 At CARB, M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50
Mode 17	0.0001 CARB>ADMM15	0.0001 M5W30 = S5W30 S15W50 > M5W30 S15W50 > S5W30	0.5162
Mode 14	0.0001 CARB>ADMM15	0.1013	0.6044
Transient	0.0001 CARB>ADMM15	0.0003 M5W30 = S5W30 S15W50 > M5W30 S15W50 > S5W30	0.0067 At ADMM15, M5W30 = S5W30 S15W50 > M5W30 S15W50 > S5W30
Weighted	0.0001 CARB>ADMM15	0.0063 S15W50 > M5W30 S15W50 > S5W30 M5W30 = S5W30	0.2231

Statistical Significance of Results
NOx

Conclusions:

- The ADMM15 fuel produced a significantly higher average NO_x than the CARB fuel at modes 20, 5, 17, transient, and weighted conditions.
- Statistically significant differences were found between the three oils at all 7 engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average NO_x levels that were similar but lower than the Synthetic 15W50 at modes 20, 10, 5, 14, transient and weighted conditions. At mode 17, Mineral 5W30 and Synthetic 5W30 produced similar but significantly higher average NO_x than the Synthetic 15W50.
- Interactions at modes 10 and 5 were significant. In both cases at the ADMM15 fuel, the Synthetic 15W50 fuel produced significantly higher average NO_x levels than either the Mineral 5W30 or the Synthetic 5W30. The Mineral 5W30 and Synthetic 5W30 were not significantly different at the ADMM15 fuel.

Table A-5. Statistical Analysis Results: P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.0001 ADMM15>CARB	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.2744
Mode 10	0.1511	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.0314 At ADMM15, S15W50 > M5W30 and S5W30
Mode 5	0.0001 ADMM15>CARB	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.0364 At ADMM15, S15W50 > M5W30 and S5W30
Mode 17	0.0009 ADMM15>CARB	0.0001 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.2225
Mode 14	0.3268	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.7459
Transient	0.0292 ADMM15>CARB	0.0054 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.1218
Weighted	0.0001 ADMM15>CARB	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.0509

Statistical Significance of Results
CO

Conclusions:

- The CARB fuel produced a significantly higher average CO than the ADMM15 fuel at modes 10, 5, 17, 14, transient, and weighted conditions.
- Statistically significant differences were found between the three oils at two engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average CO levels that were similar but higher than the Synthetic 15W50 at mode 10. At mode 17, Mineral 5W30 and Synthetic 5W30 produced similar but significantly lower average CO than the Synthetic 15W50.
- The interaction at the weighted condition was significant. In this case at the ADMM15 fuel, the Synthetic 15W50 fuel produced significantly higher average CO levels than either the Mineral 5W30 or the Synthetic 5W30. The Mineral 5W30 and Synthetic 5W30 were not significantly different at the ADMM15 fuel.

Table A-6. Statistical Analysis Results: P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.6491	0.3037	0.6102
Mode 10	0.0001 CARB>ADMM15	0.0001 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.1580
Mode 5	0.0005 CARB>ADMM15	0.8782	0.0743
Mode 17	0.0017 CARB>ADMM15	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.7351
Mode 14	0.0011 CARB>ADMM15	0.1470	0.3334
Transient	0.0001 CARB>ADMM15	0.0564	0.0096 At ADMM15, S15W50 > S5W30 and M5W30
Weighted	0.0001 CARB>ADMM15	0.6943	0.1809

Statistical Significance of Results
HC

Conclusions:

- The CARB fuel produced a significantly higher average HC than the ADMM15 fuel at mode 10, transient, and weighted conditions.
- Statistically significant differences were found between the three oils at 4 engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average HC levels that were similar but higher than the Synthetic 15W50 at mode 17 and the weighted condition. At modes 10 and 14, Mineral 5W30 produced significantly higher average HC than the Synthetic 15W50.
- No significant interactions were found at any of the operating conditions.

Table A-7. Statistical Analysis Results: P-values and Multiple Comparison Tests

Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.1371	0.1134	0.1134
Mode 10	0.0002 CARB>ADMM15	0.0096 M5W30 > S15W50	0.1532
Mode 5	0.4502	0.4745	0.0698
Mode 17	0.0877	0.0003 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.1979
Mode 14	0.3465	0.0016 M5W30 > S15W50	0.0663
Transient	0.0001 CARB>ADMM15	0.0653	0.6620
Weighted	0.0010 CARB>ADMM15	0.0079 M5W30 = S5W30 M5W30 > S15W50 S5W30 > S15W50	0.1147

Statistical Significance of Results
CO2

Conclusions:

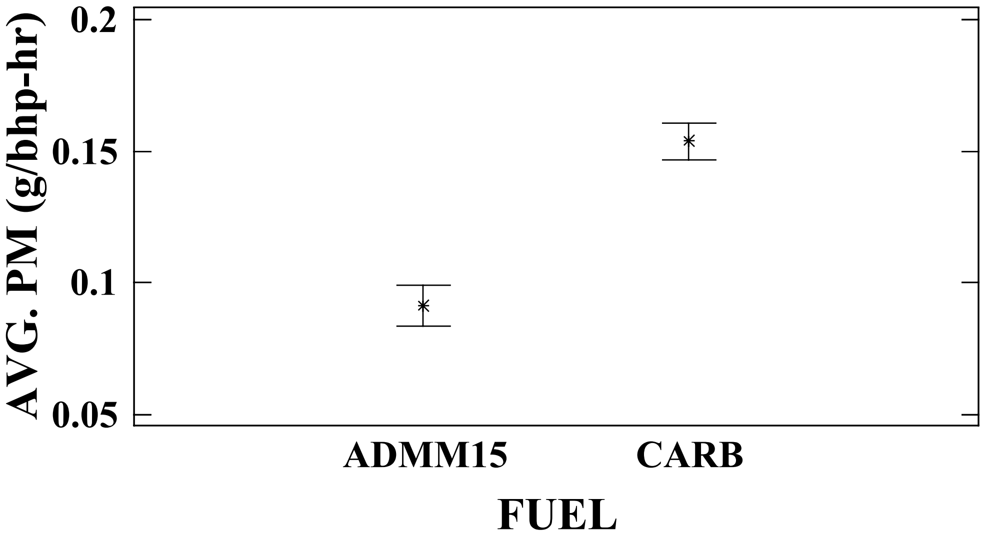
- The CARB fuel produced a significantly higher average CO2 than the ADMM15 fuel at Mode 20 only.
- Statistically significant differences were found between the three oils at all 7 engine operating conditions. Mineral 5W30 and Synthetic 5W30 produced average CO2 levels that were similar but lower than the Synthetic 15W50 at modes 20, 10, 5, 14, transient, and weighted. At mode 17, Mineral 5W30 produced significantly lower average CO2 than the Synthetic 15W50.
- No significant interactions were found at any of the operating conditions.

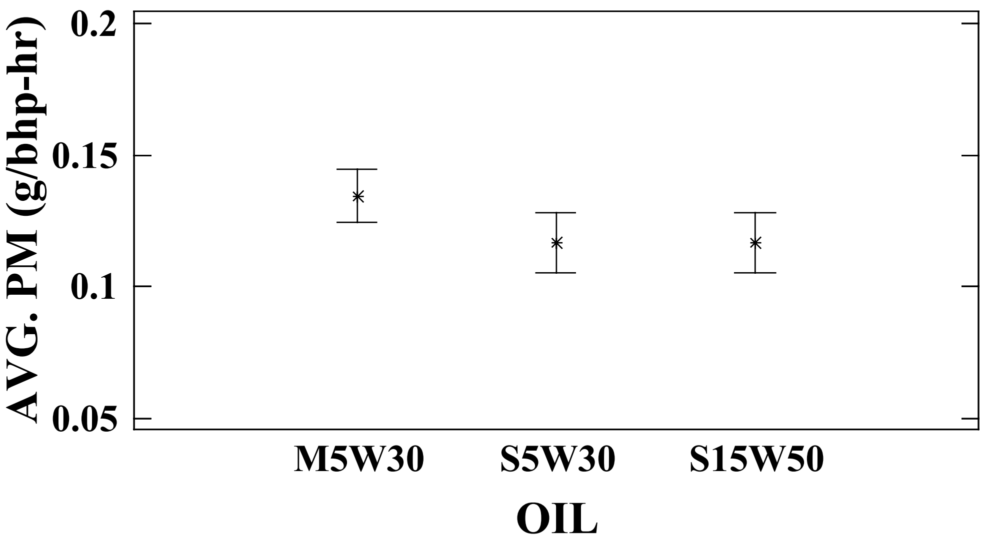
Table A-8. Statistical Analysis Results: P-values and Multiple Comparison Tests

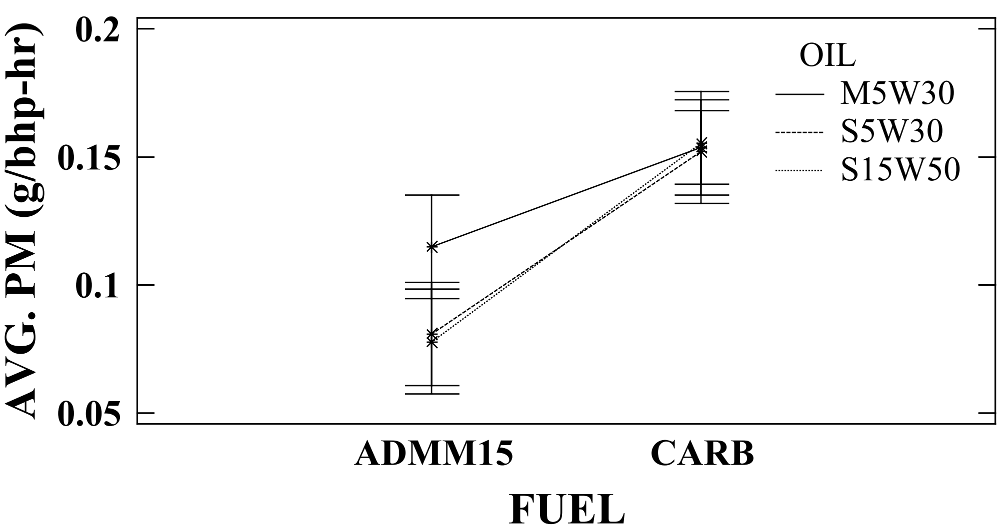
Operating Condition	Fuel	Oil	Fuel x Oil Interaction
Mode 20	0.0281 CARB>ADMM15	0.0034 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.9804
Mode 10	0.3490	0.0004 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.4682
Mode 5	0.5844	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.4907
Mode 17	0.5490	0.0058 M5W30 < S15W50	0.3605
Mode 14	0.9992	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.0506
Transient	0.9277	0.0034 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.0717
Weighted	0.7912	0.0001 M5W30 = S5W30 M5W30 < S15W50 S5W30 < S15W50	0.1776

APPENDIX B
Graphical Results of Statistical Analysis

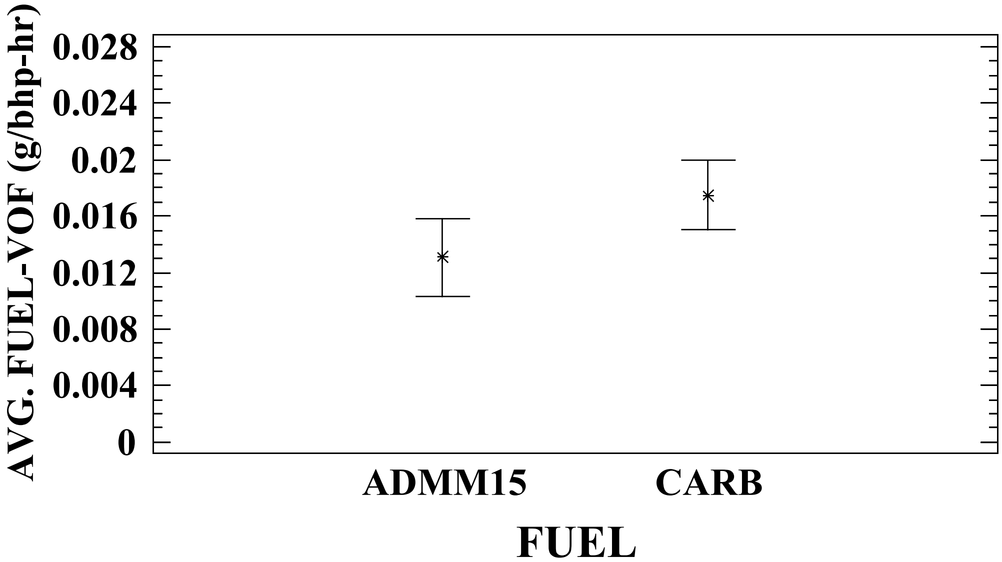
Mode 20 (1000 rpm, 75 ft-lb)
Particulate (PM)

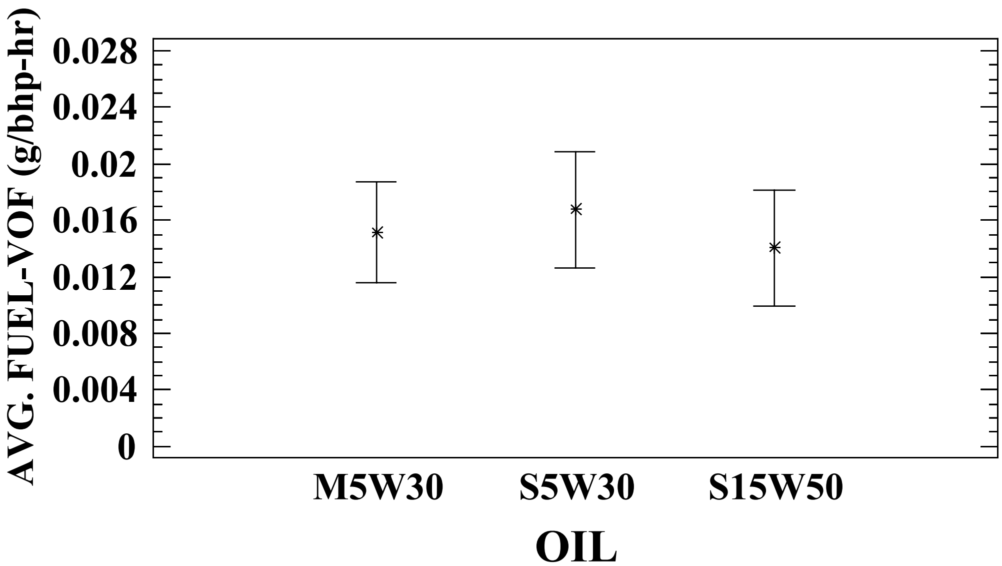


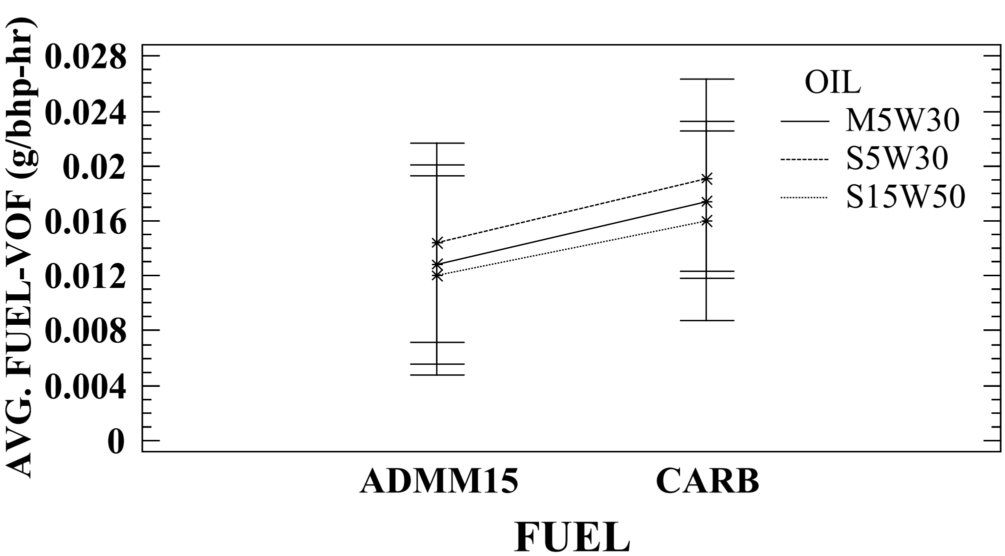




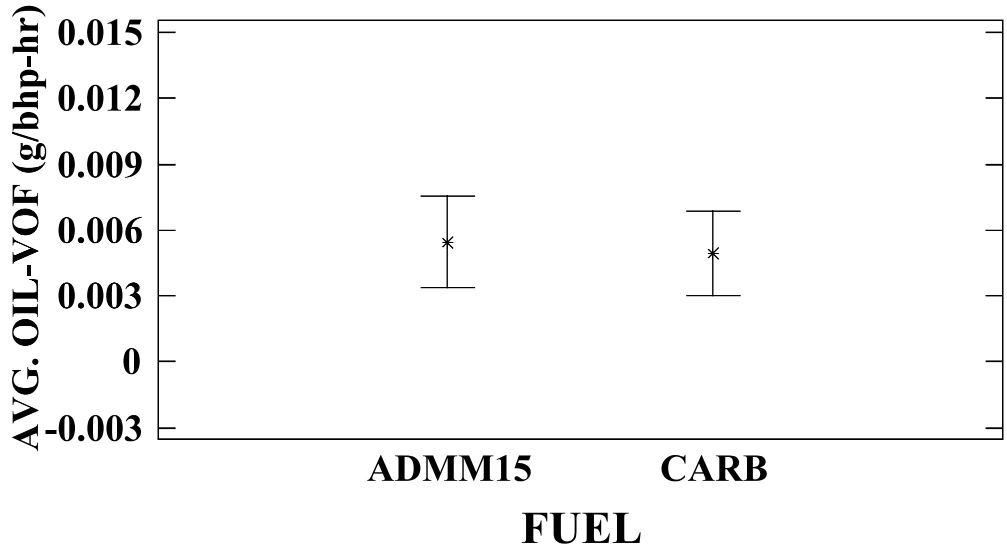
Mode 20 (1000 rpm, 75 ft-lb)
Fuel-VOF

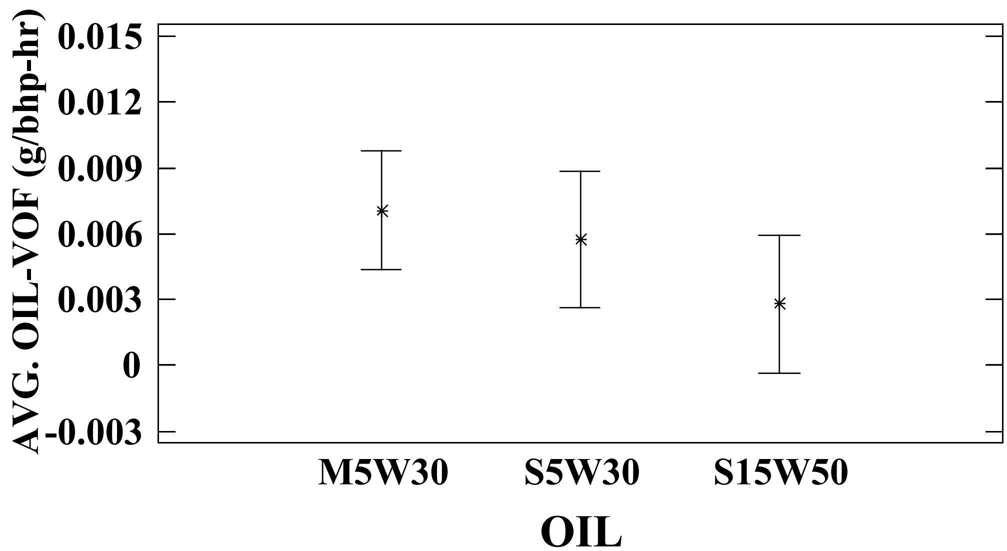


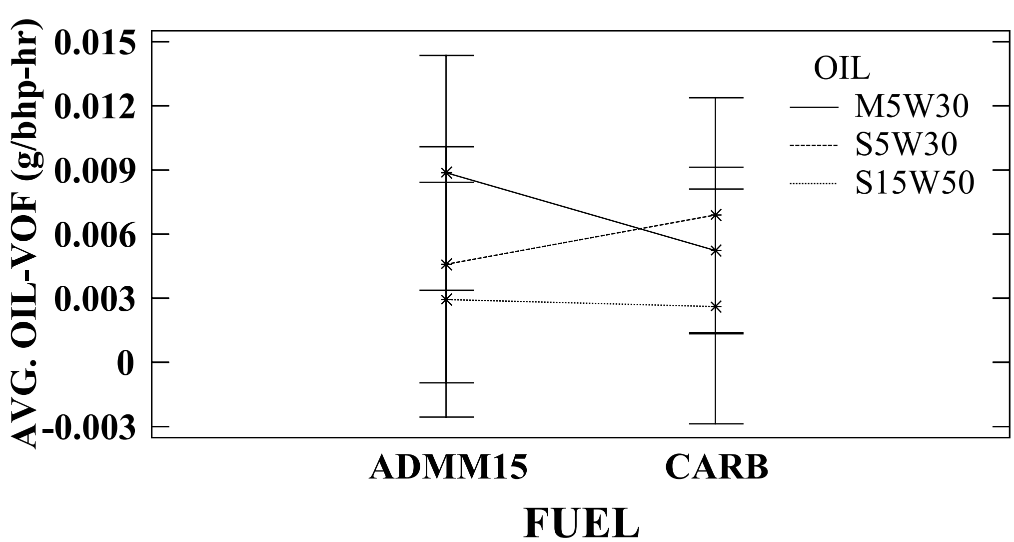




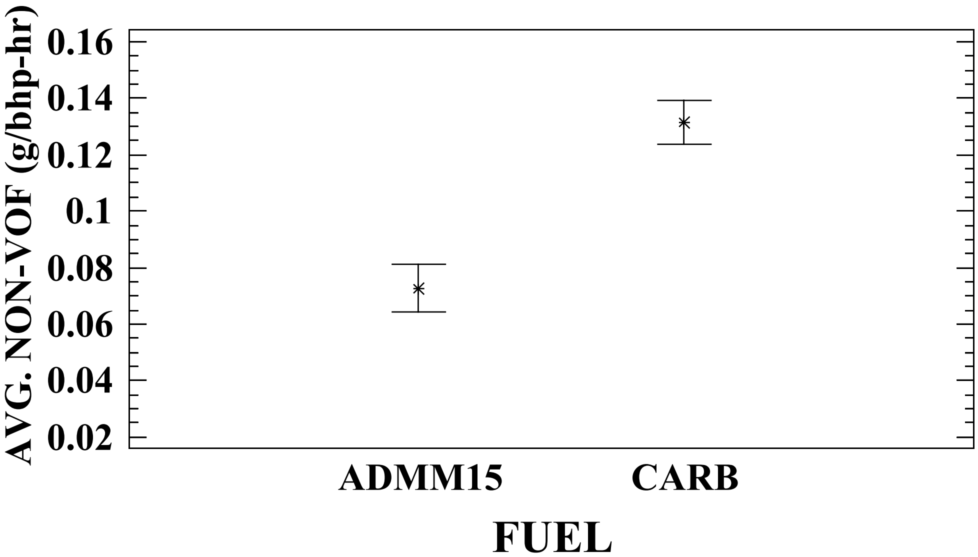
Mode 20 (1000 rpm, 75 ft-lb)
Oil-VOF

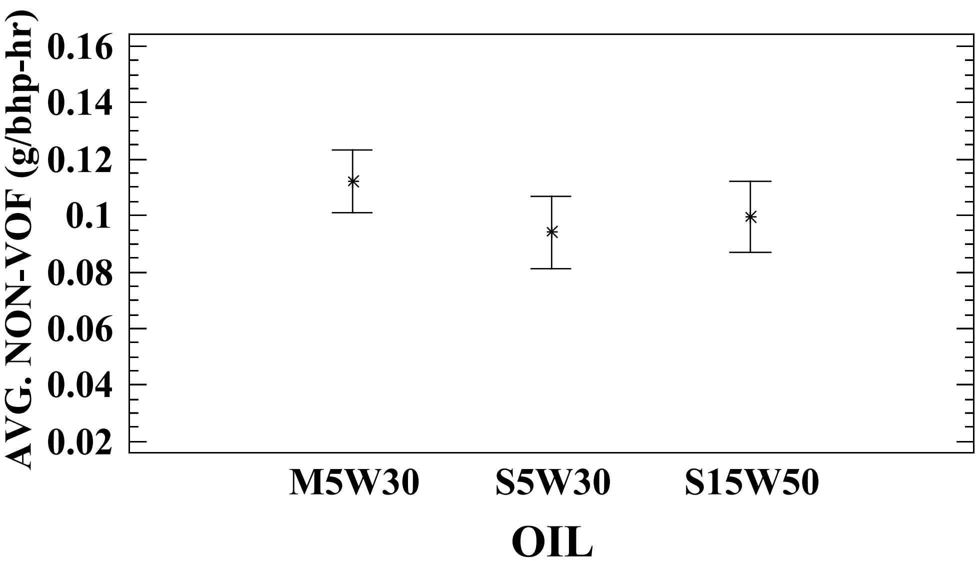


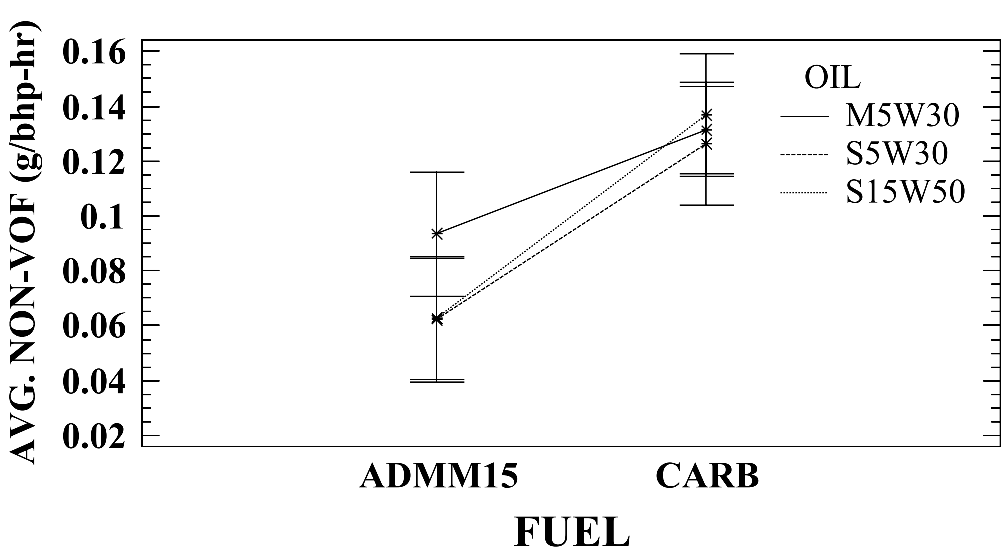




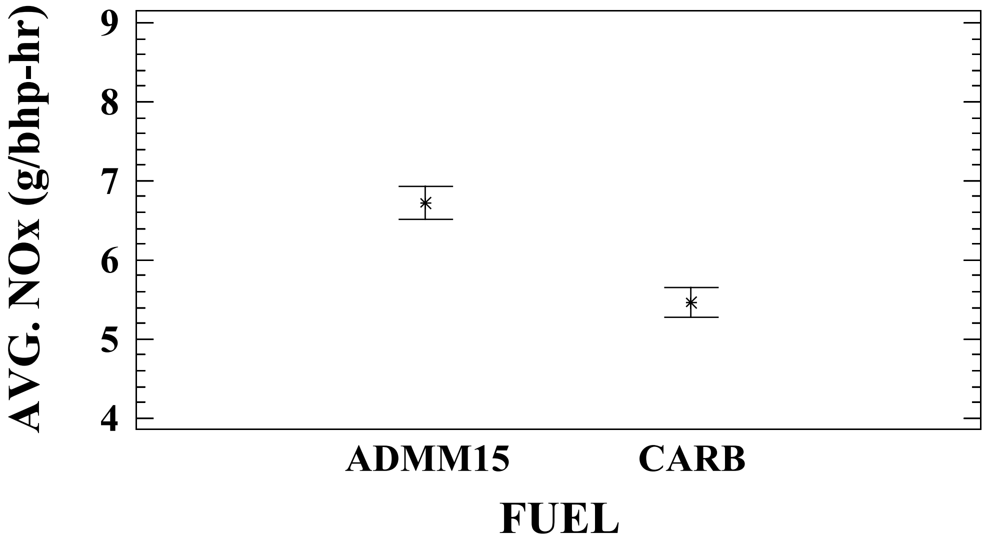
Mode 20 (1000 rpm, 75 ft-lb)
Non-VOF

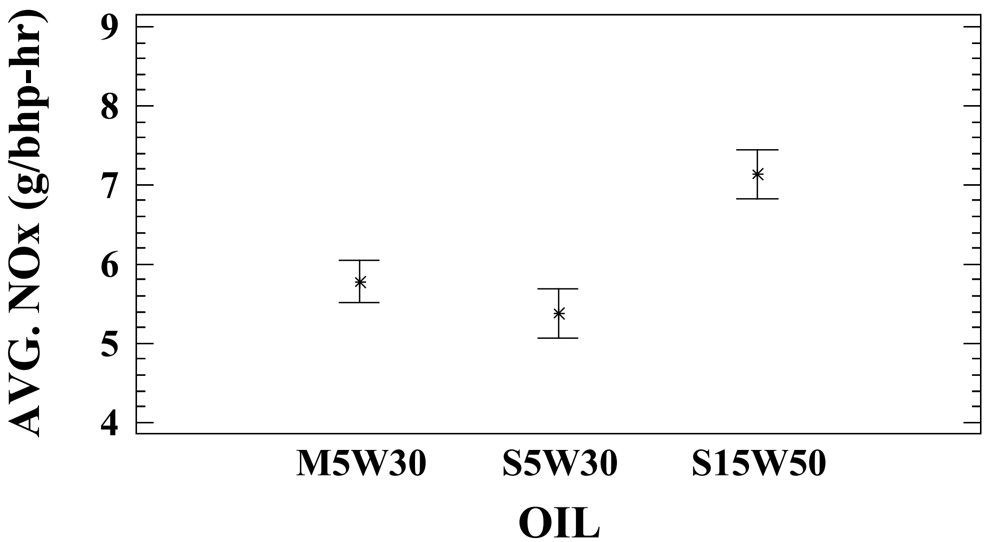


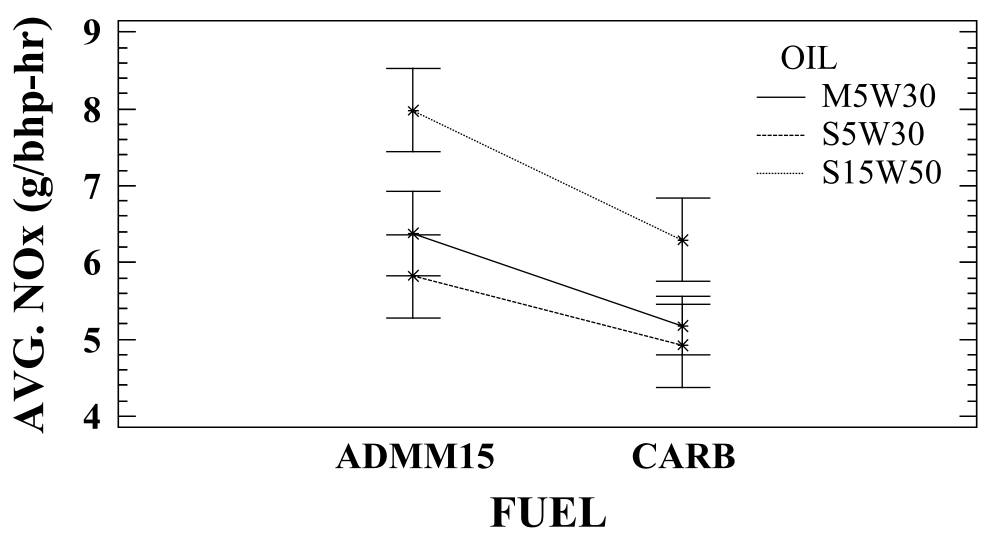




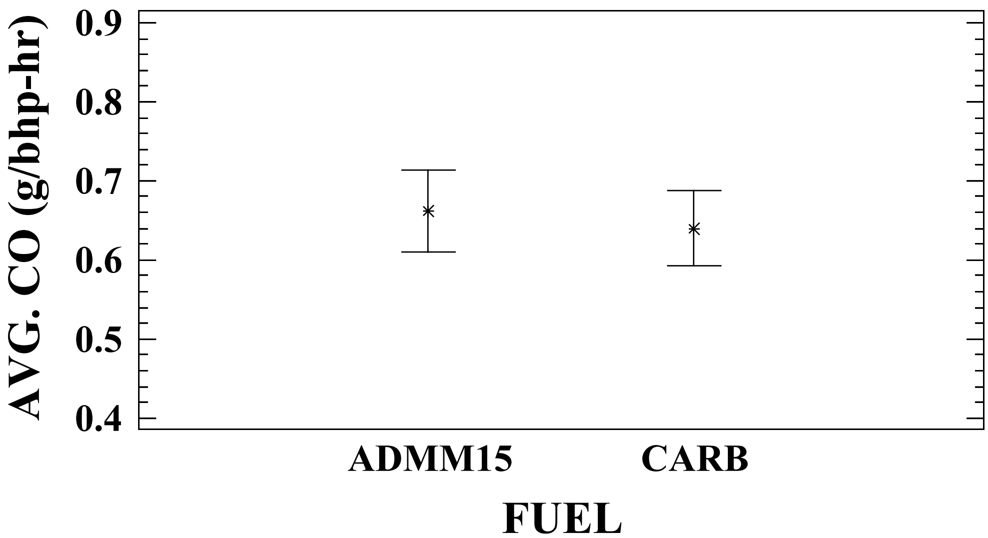
Mode 20 (1000 rpm, 75 ft-lb)
NOx

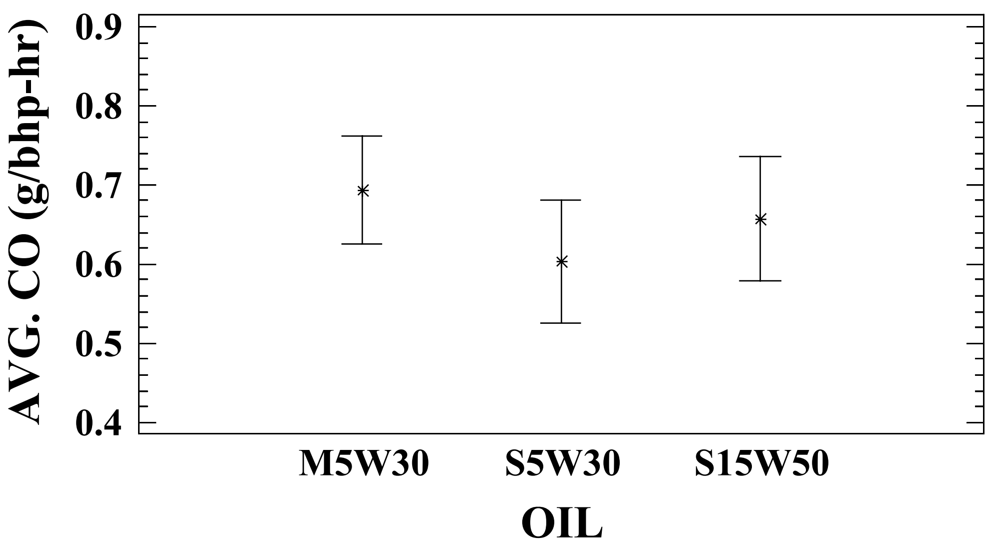


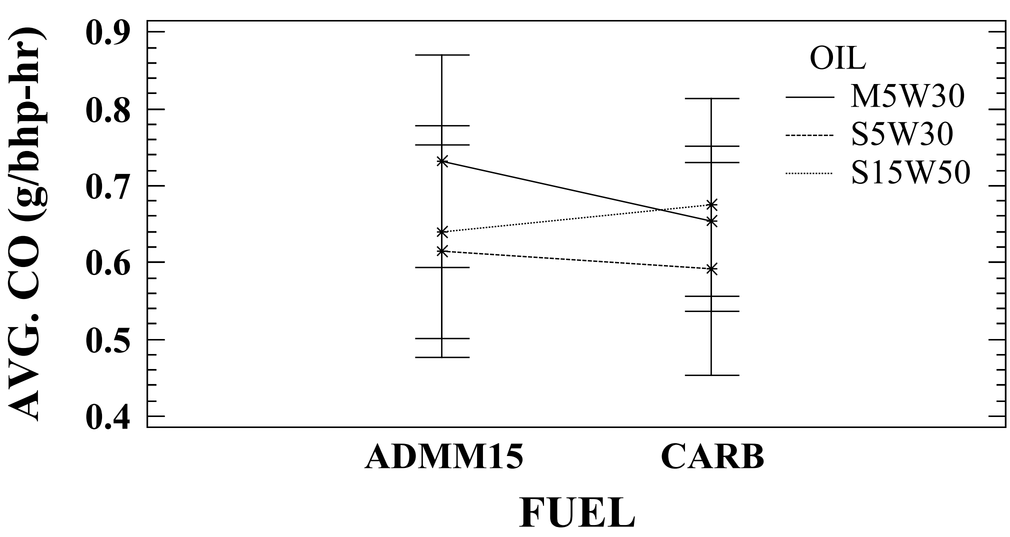




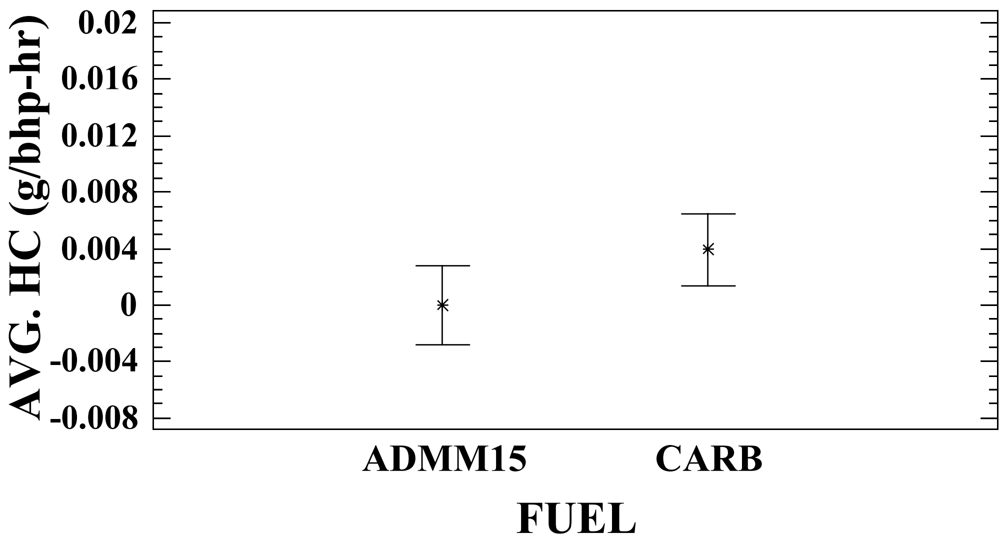
Mode 20 (1000 rpm, 75 ft-lb)
CO

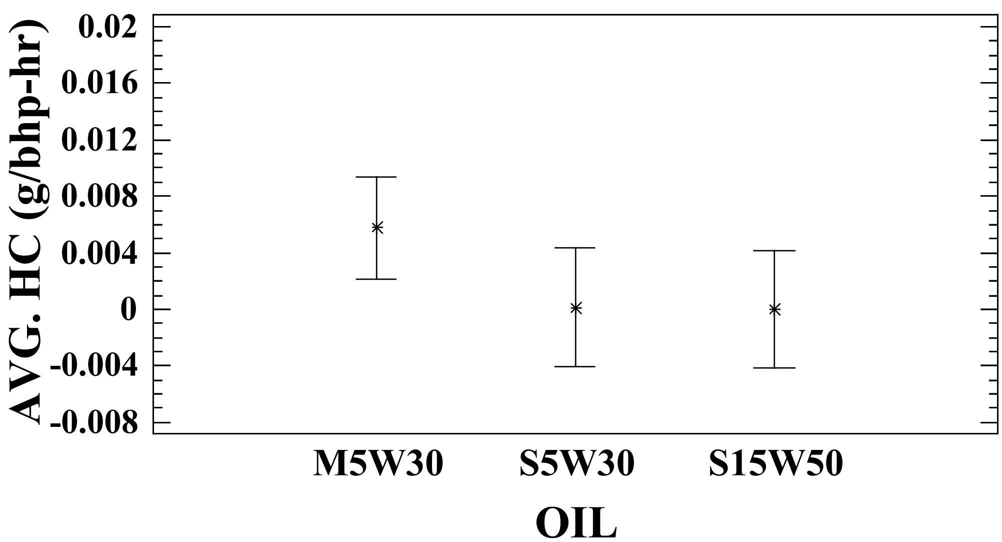


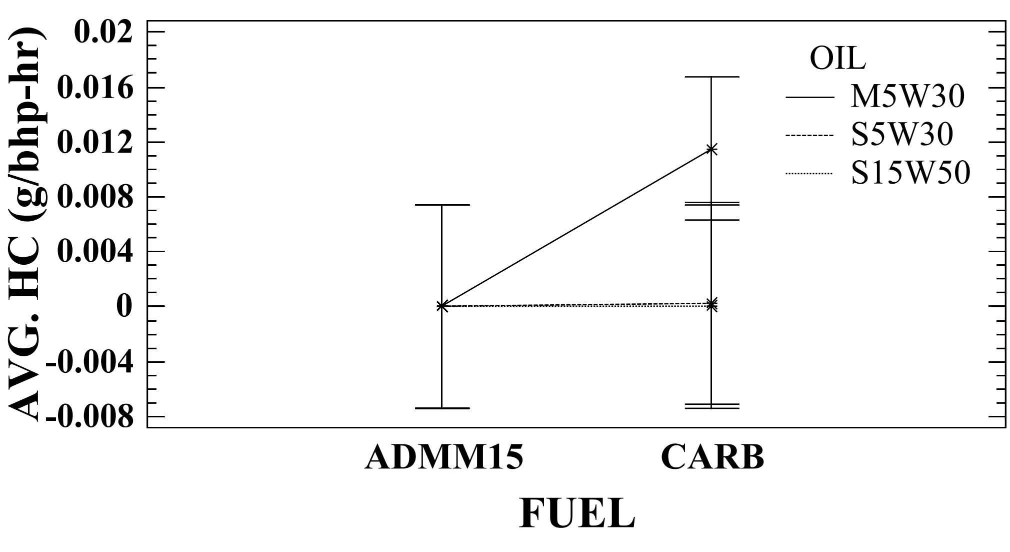




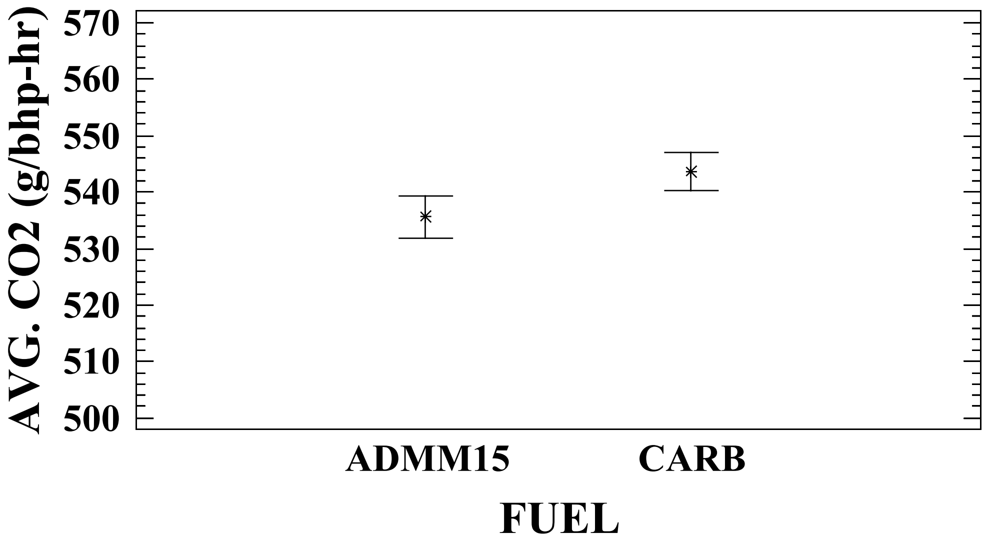
Mode 20 (1000 rpm, 75 ft-lb)
HC

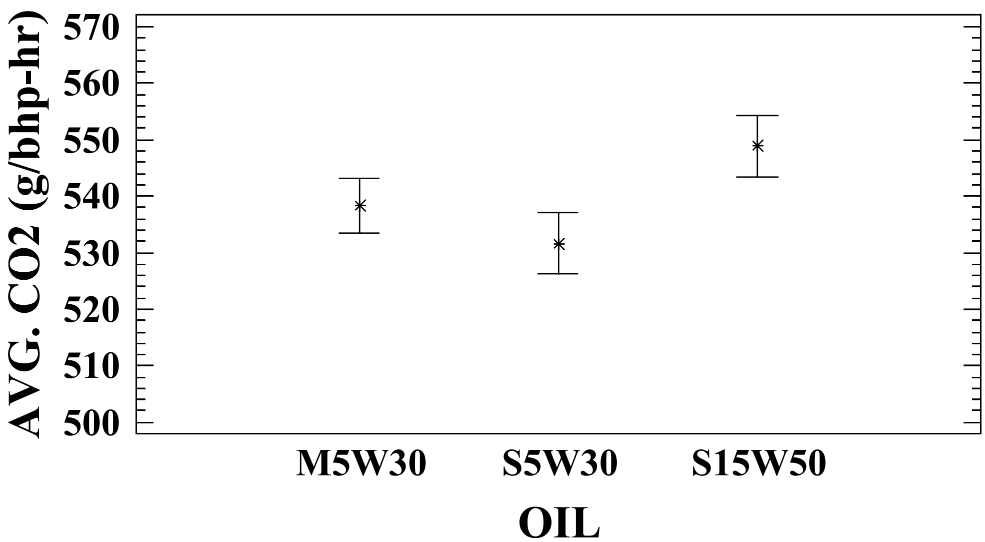


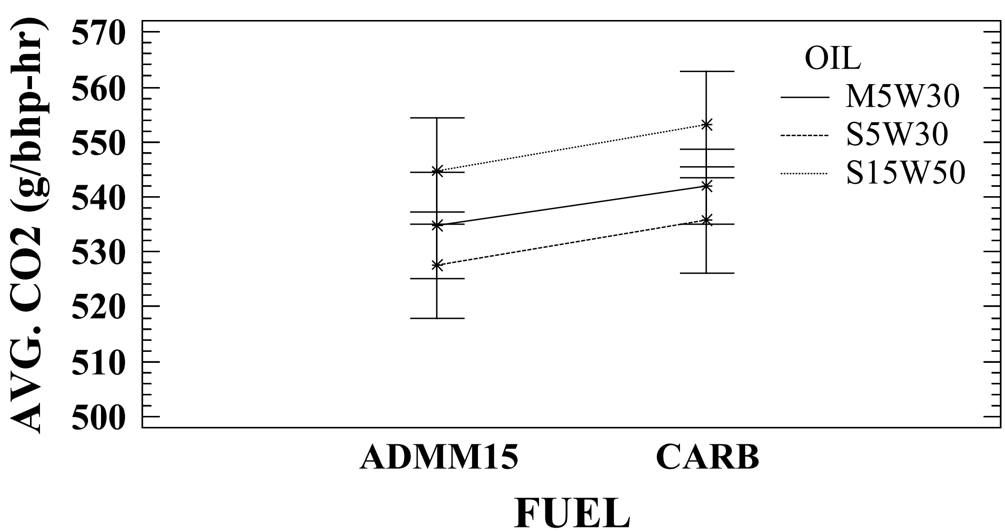




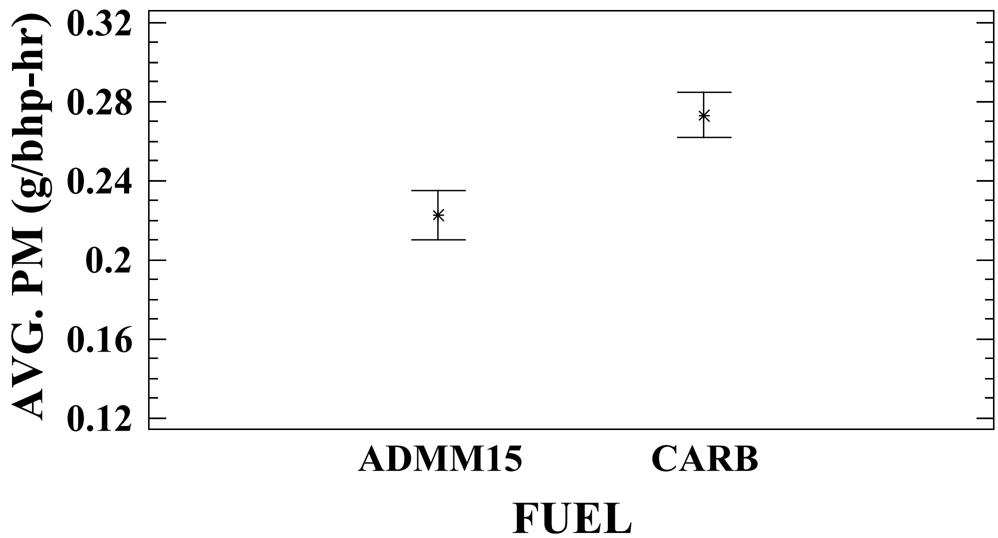
Mode 20 (1000 rpm, 75 ft-lb)
CO2

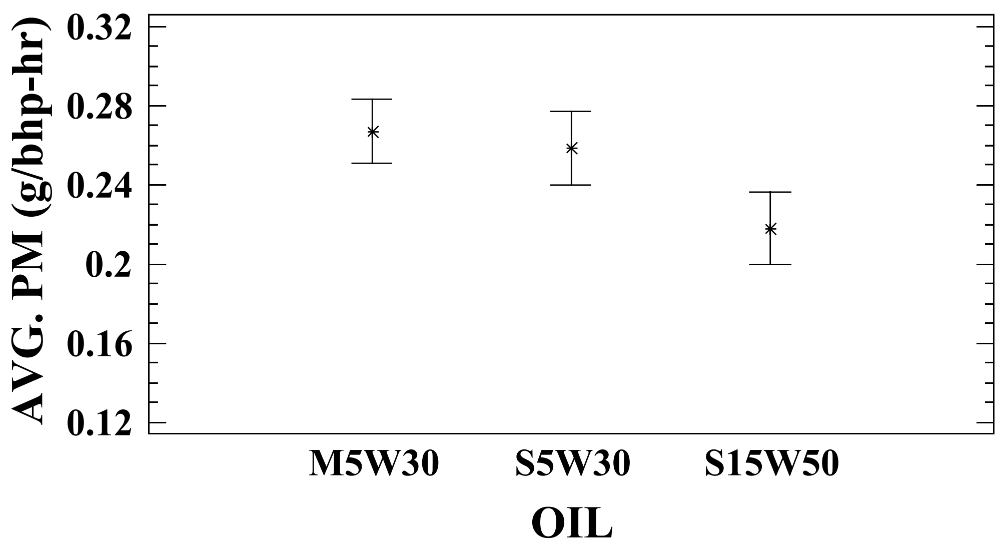


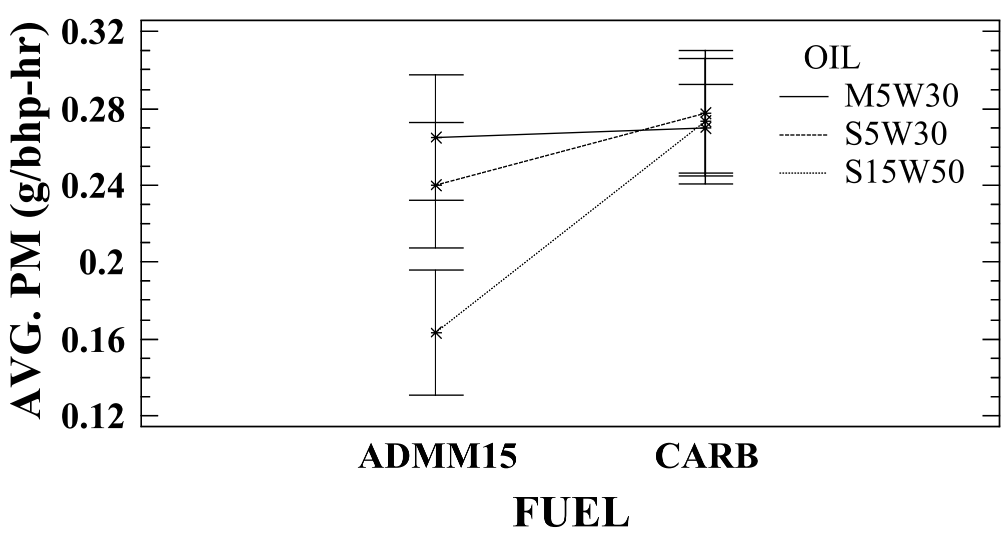




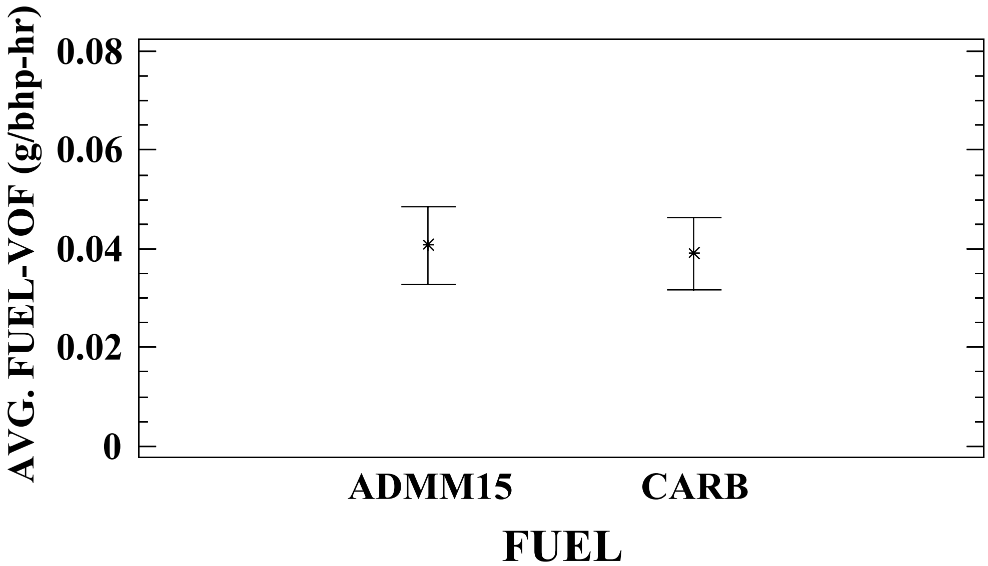
Mode 10 (2000 rpm, 25 ft-lb)
Particulate (PM)

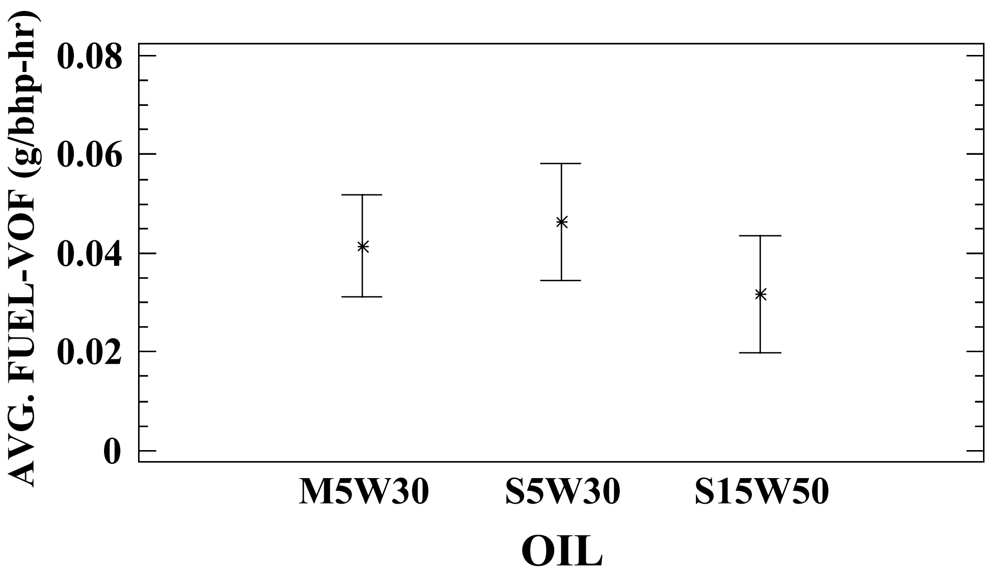


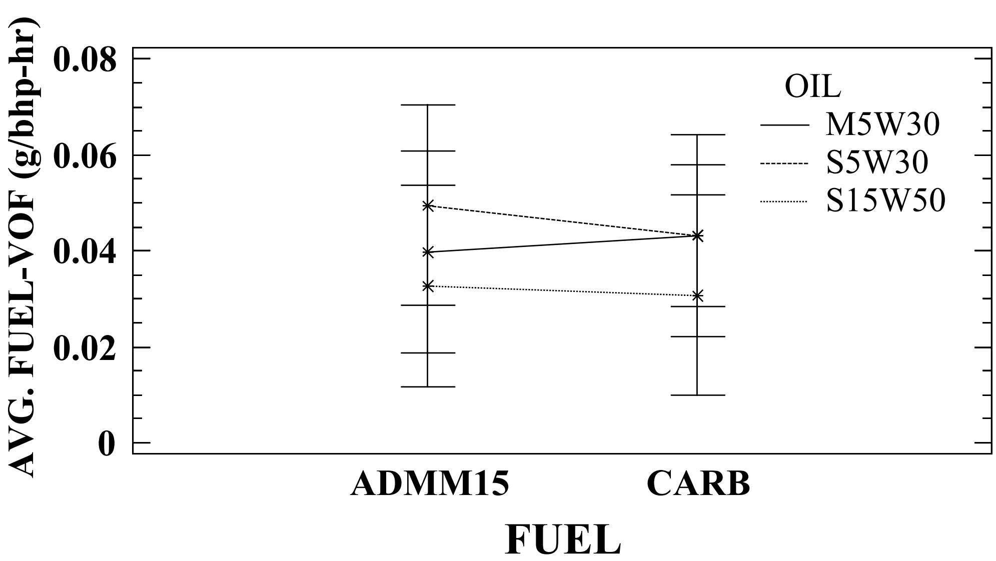




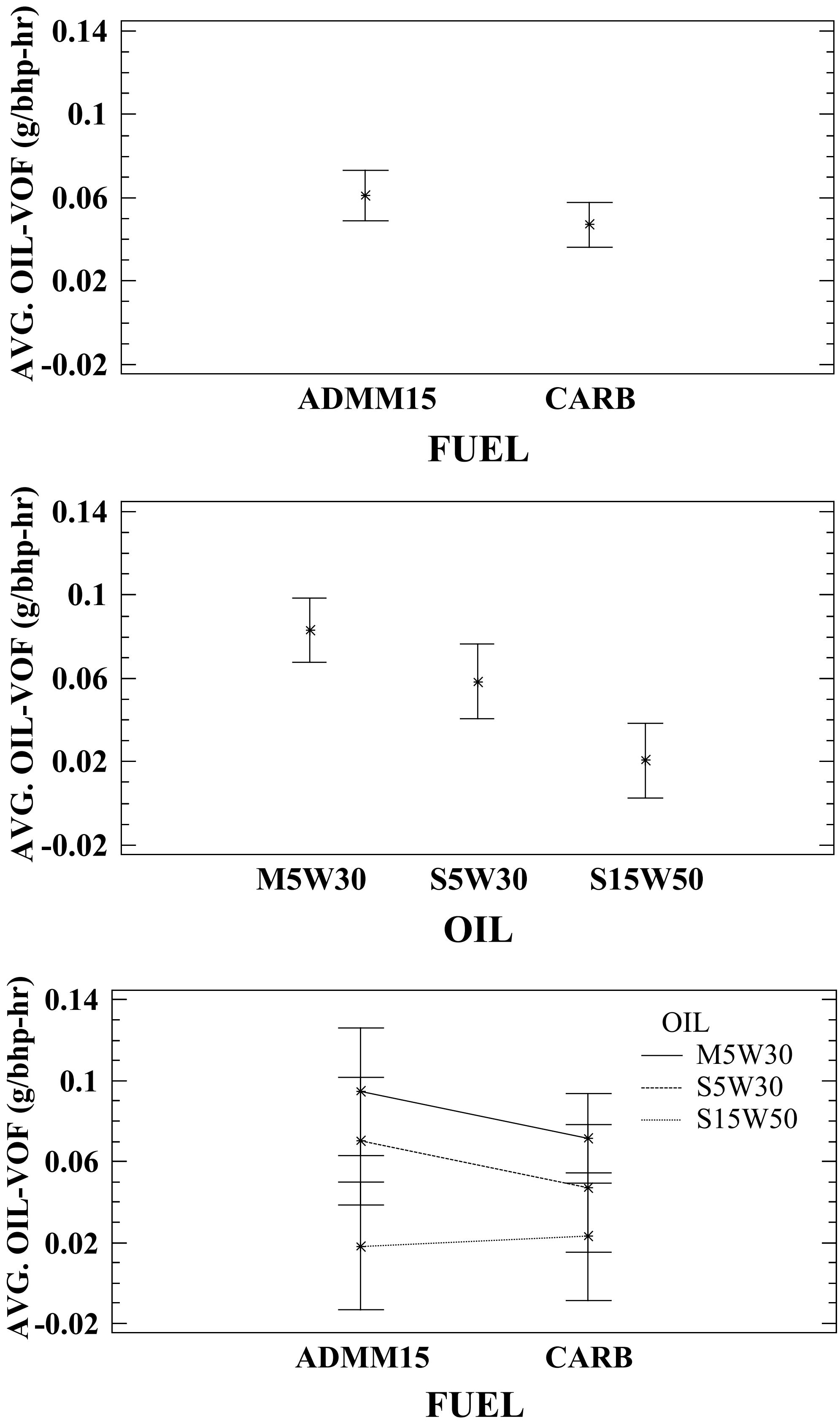
Mode 10 (2000 rpm, 25 ft-lb)
Fuel-VOF



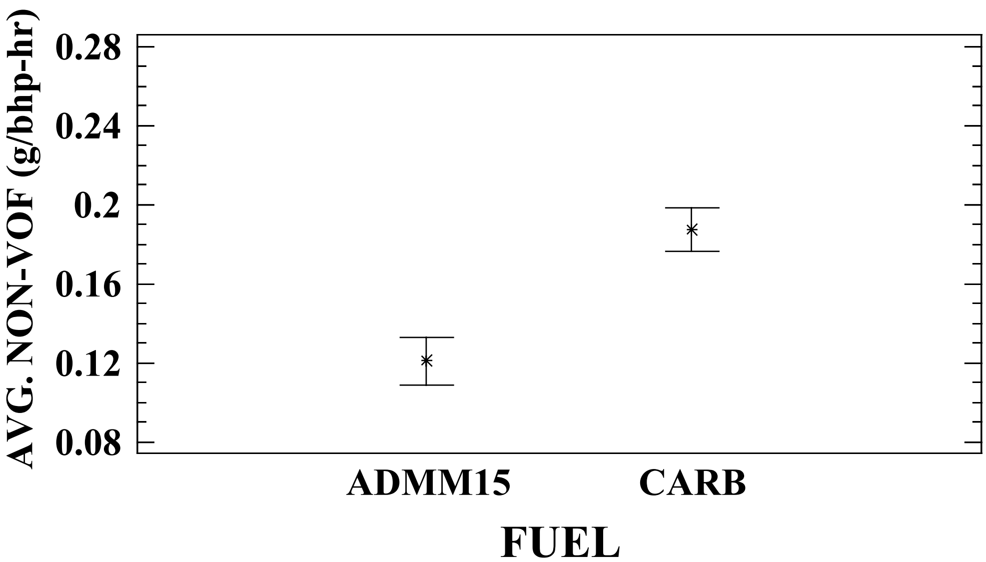


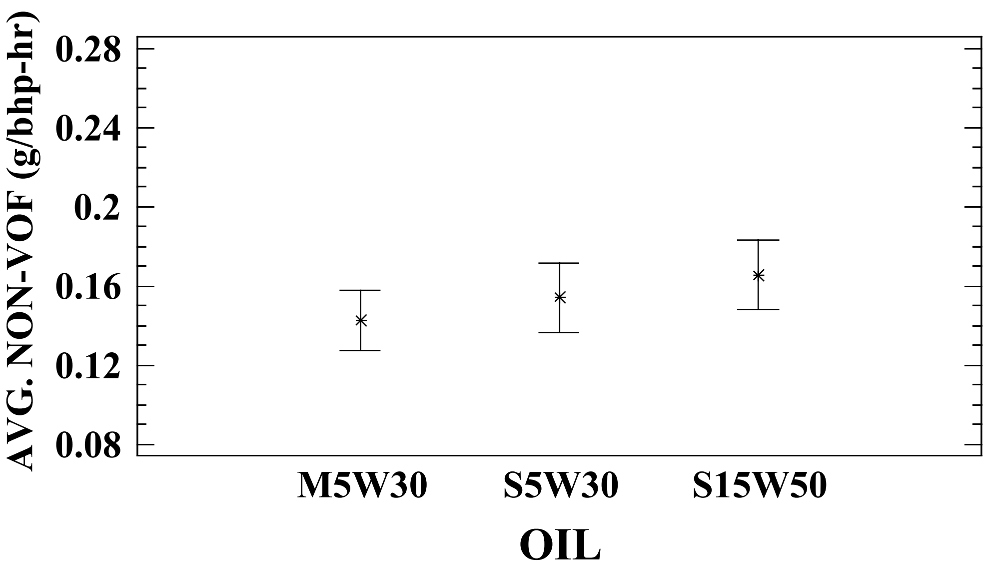


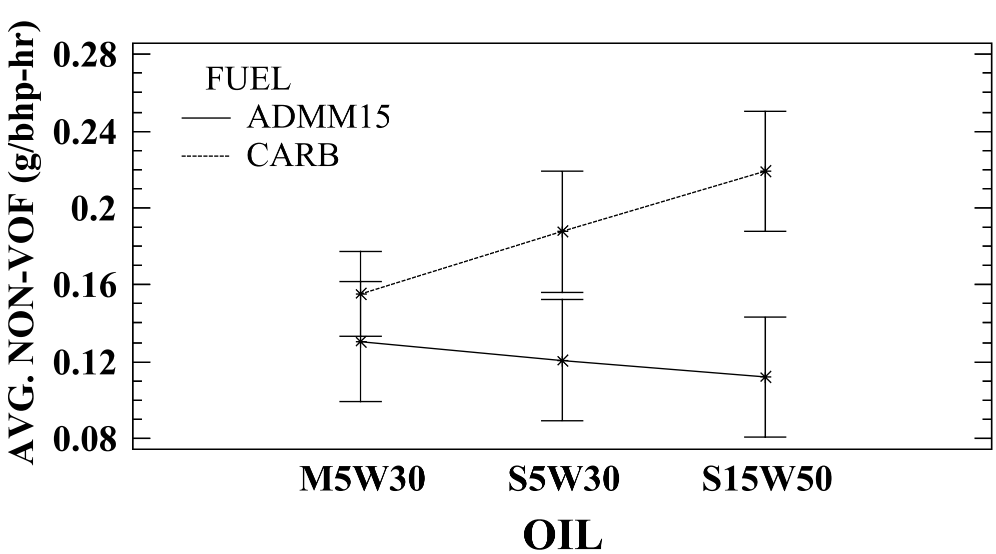
Mode 10 (2000 rpm, 25 ft-lb)
Oil-VOF



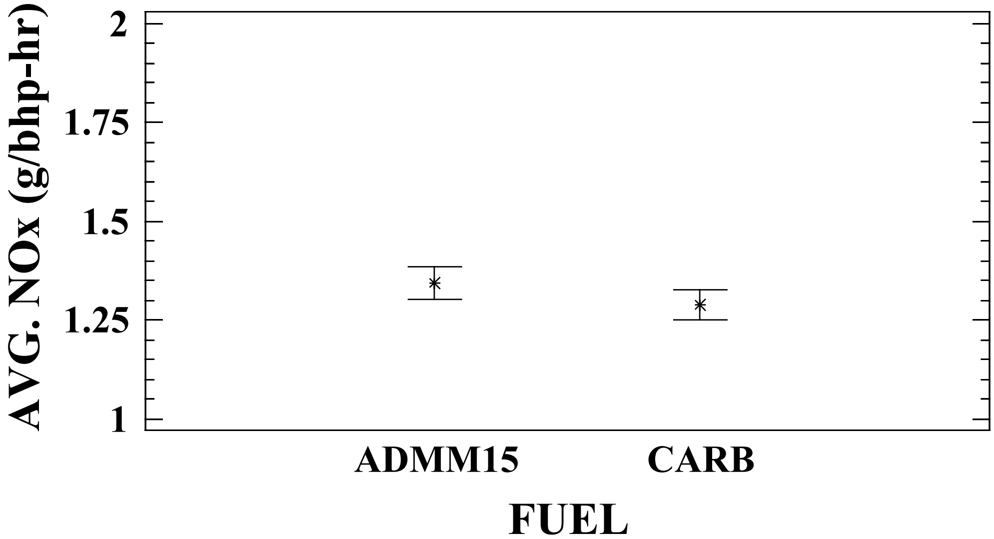
Mode 10 (2000 rpm, 25 ft-lb)
Non-VOF

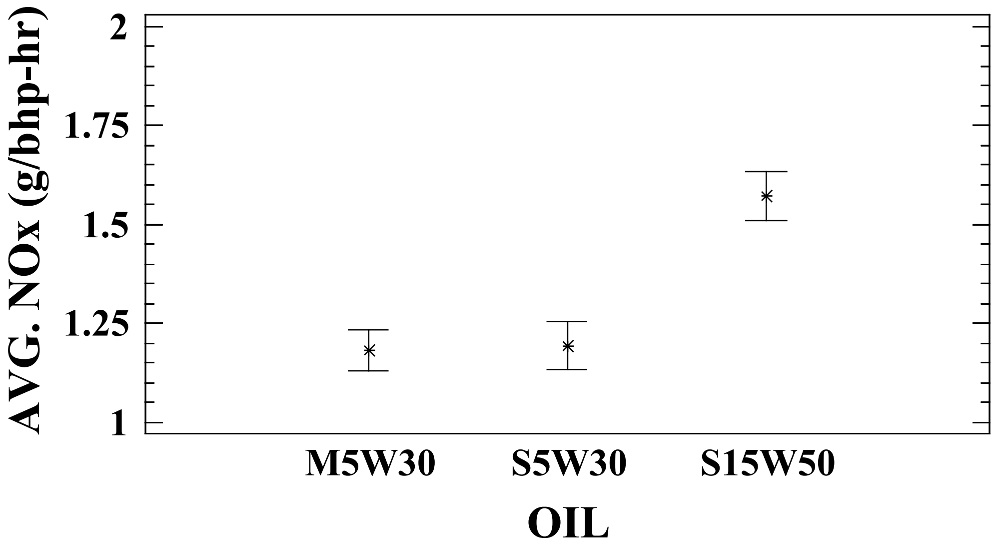


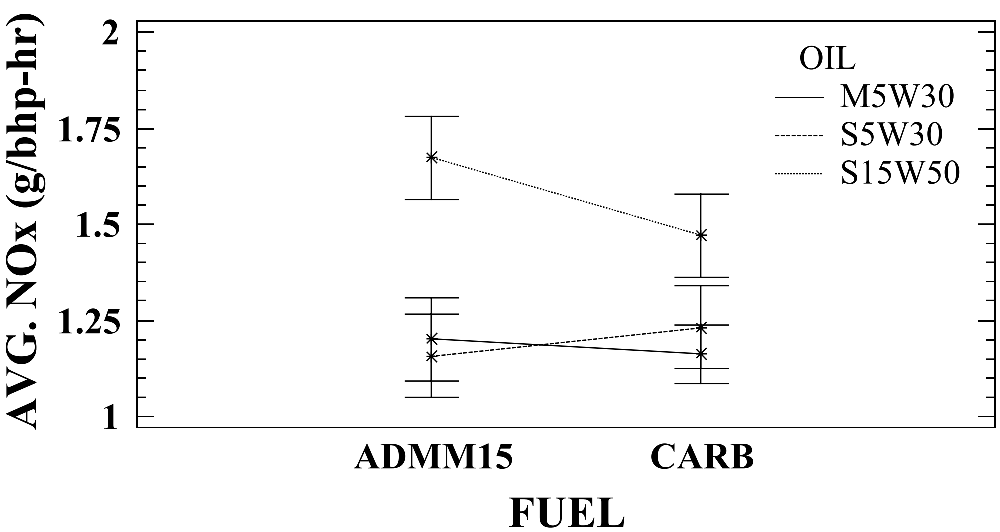




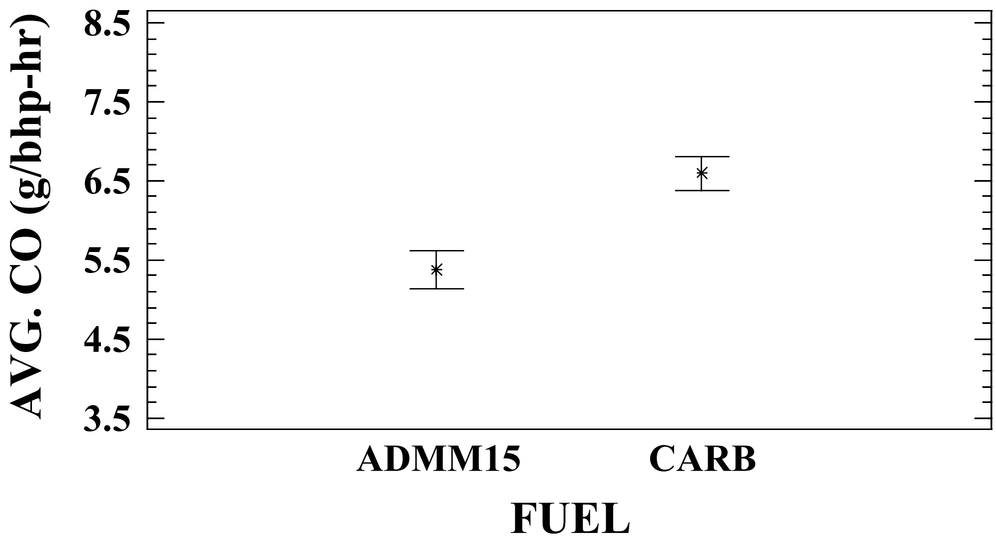
Mode 10 (2000 rpm, 25 ft-lb)
NOx

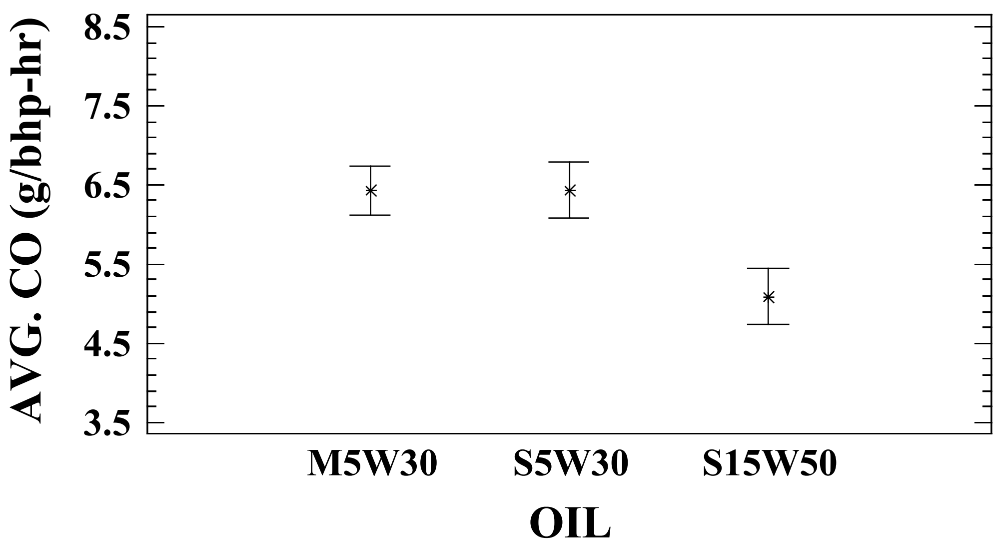


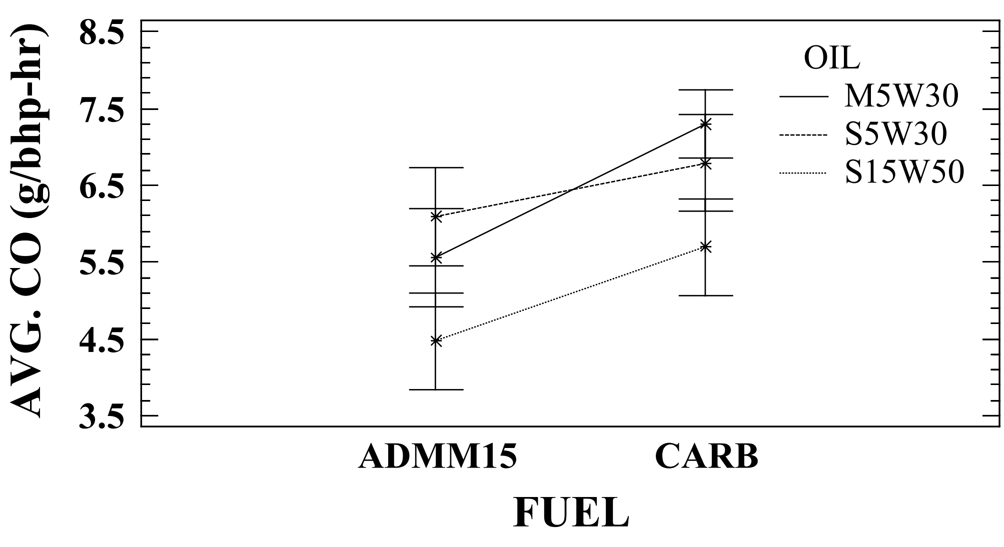




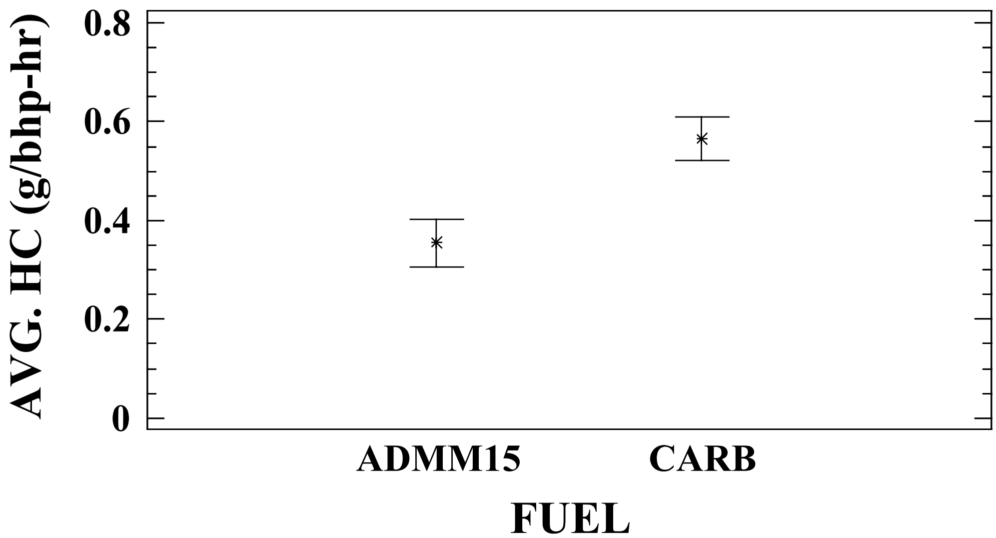
Mode 10 (2000 rpm, 25 ft-lb)
CO

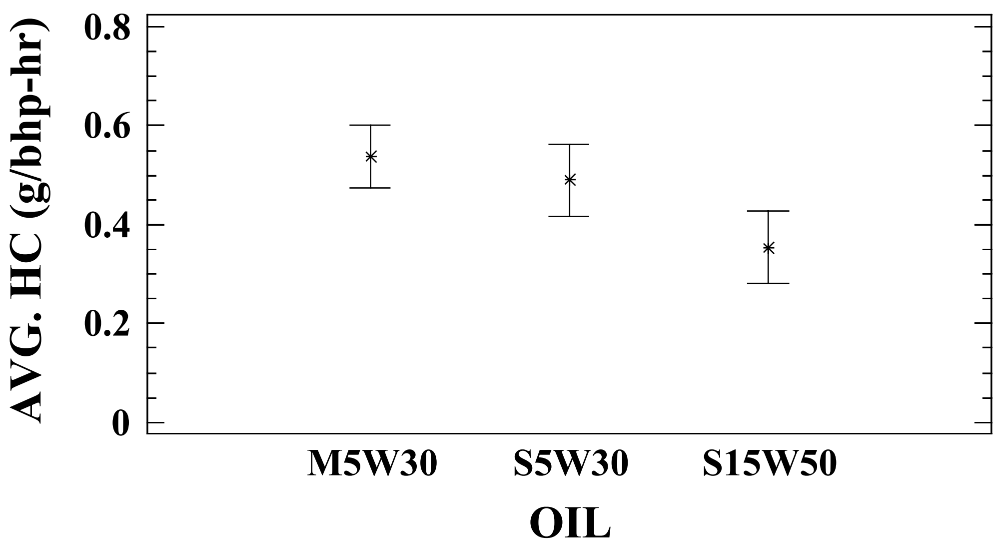


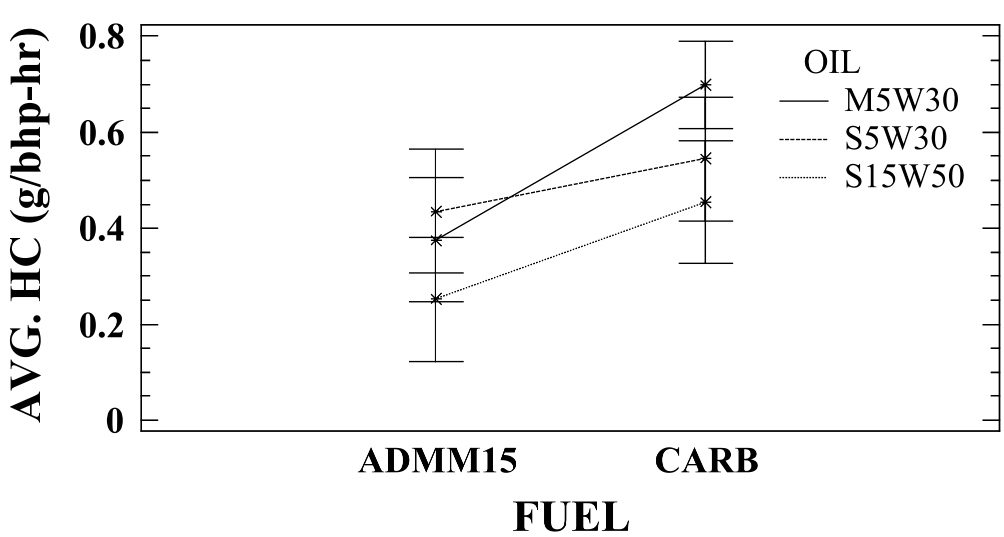




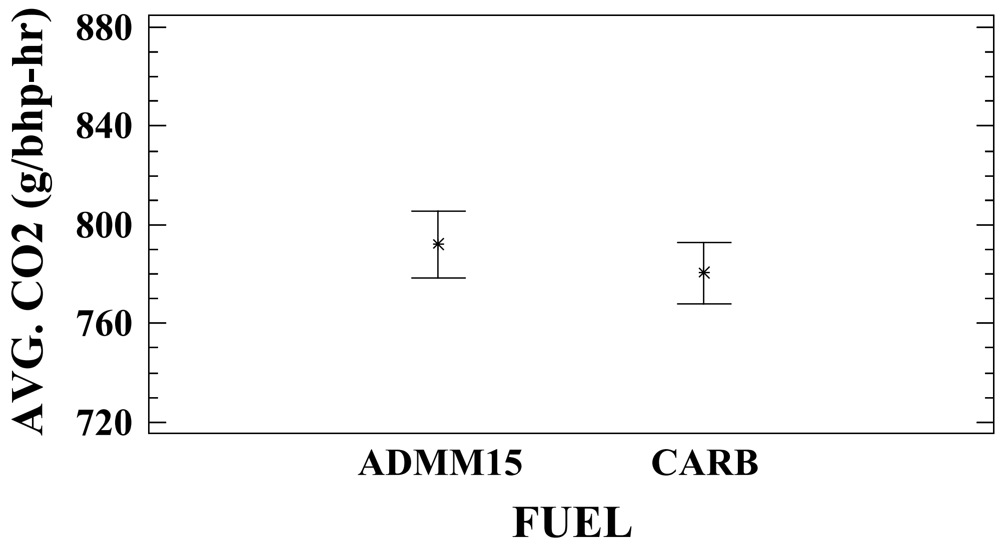
Mode 10 (2000 rpm, 25 ft-lb)
HC

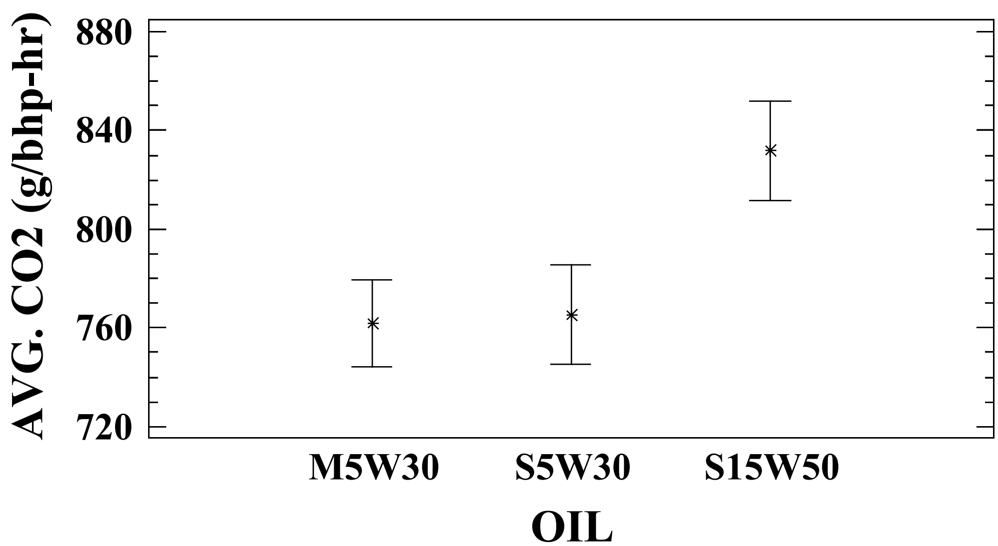


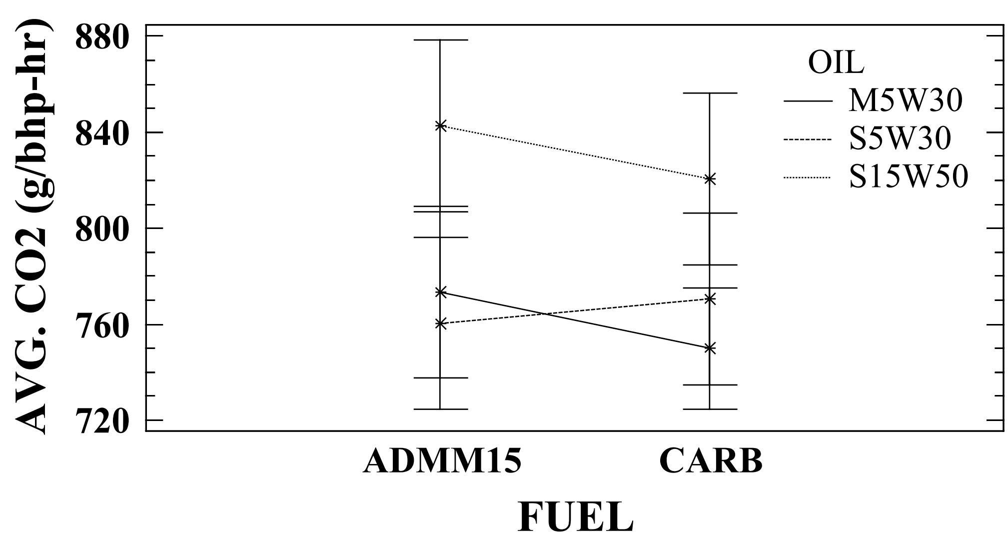




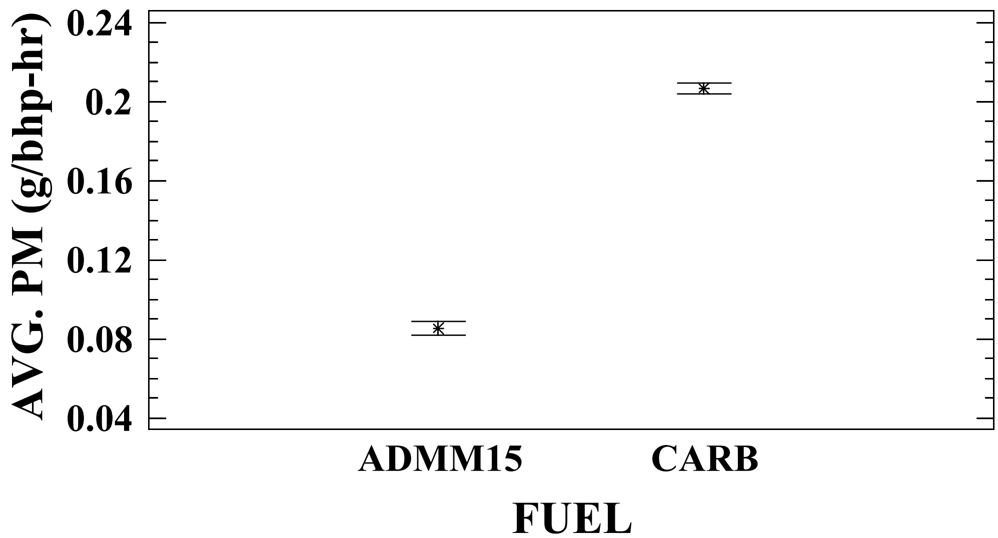
Mode 10 (2000 rpm, 25 ft-lb)
CO2

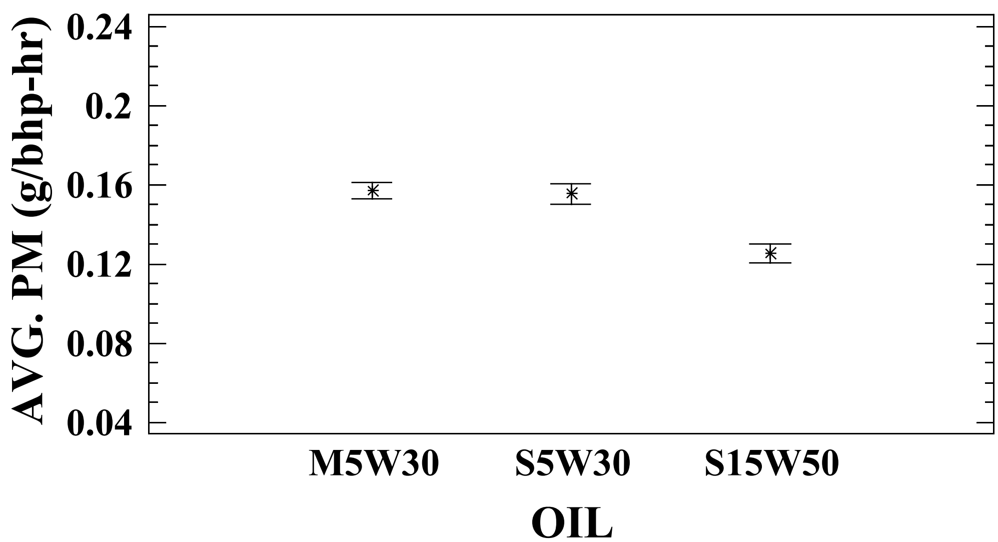


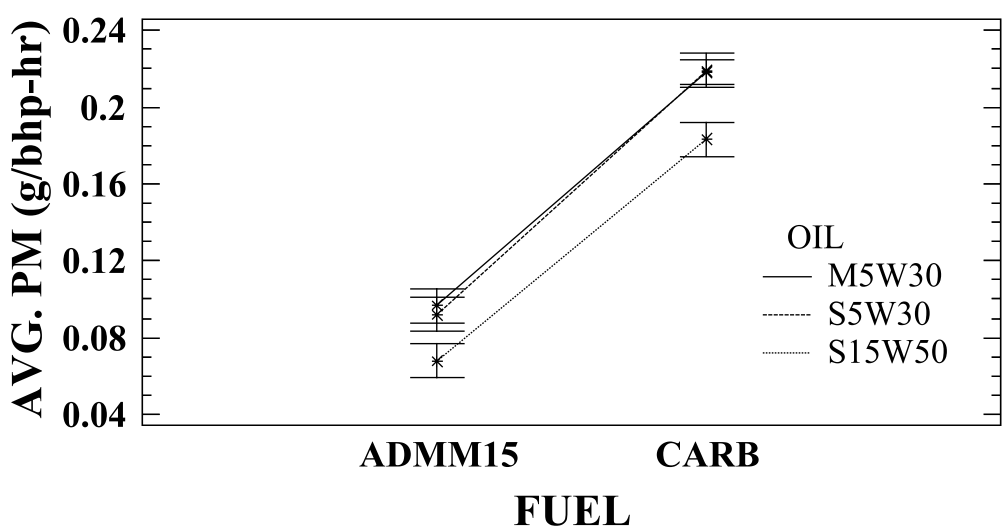




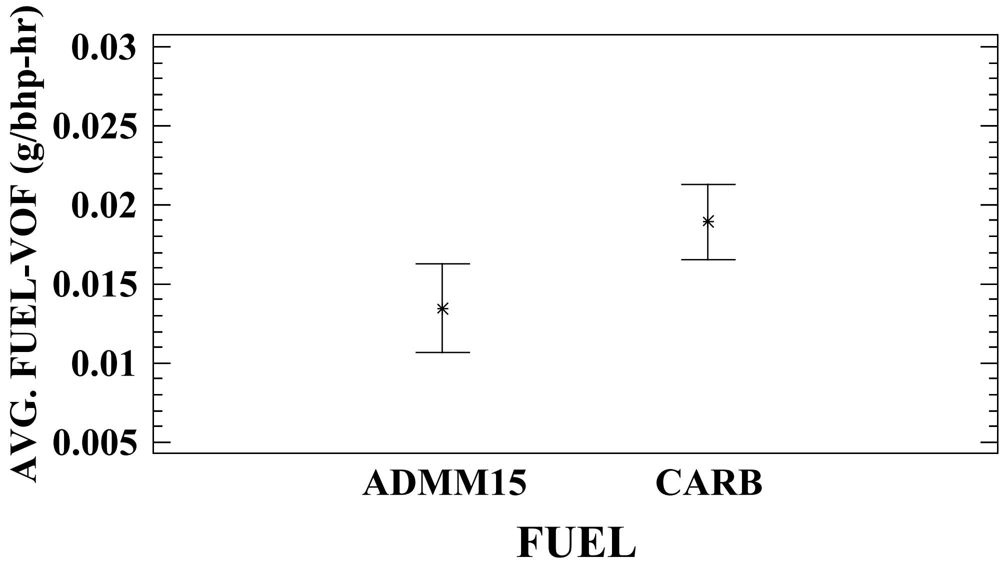
Mode 5 (2600 rpm, 111 ft-lb)
Particulate (PM)

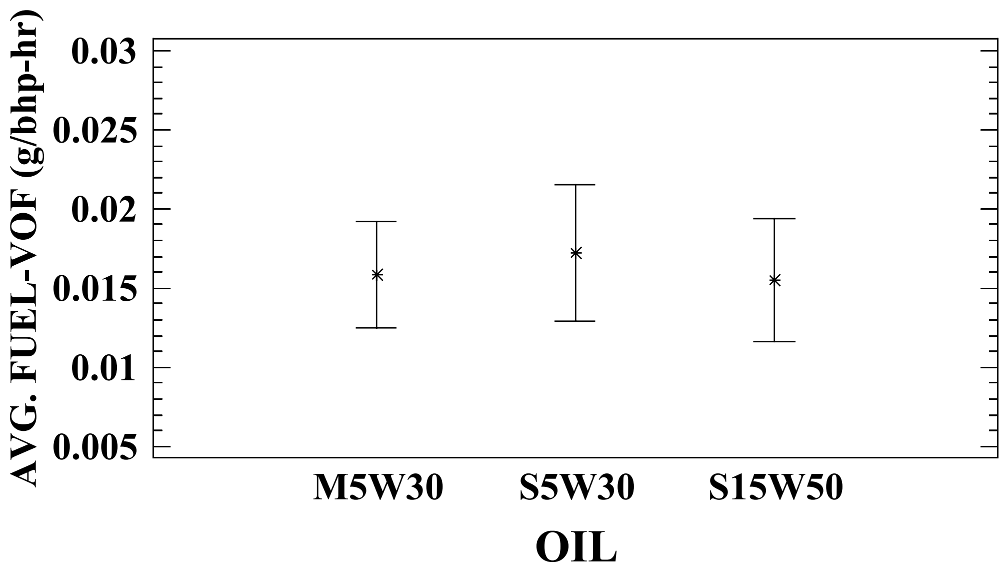


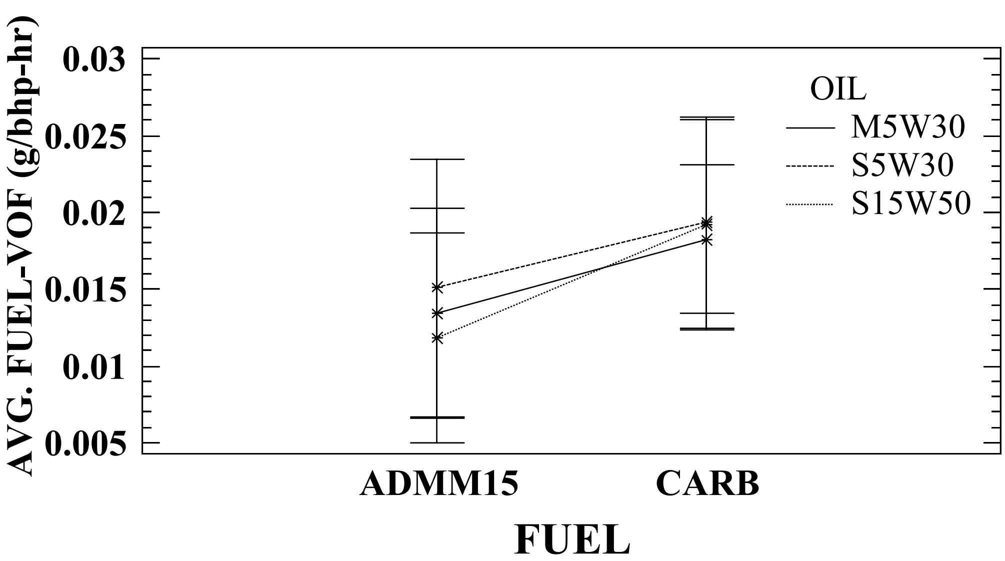




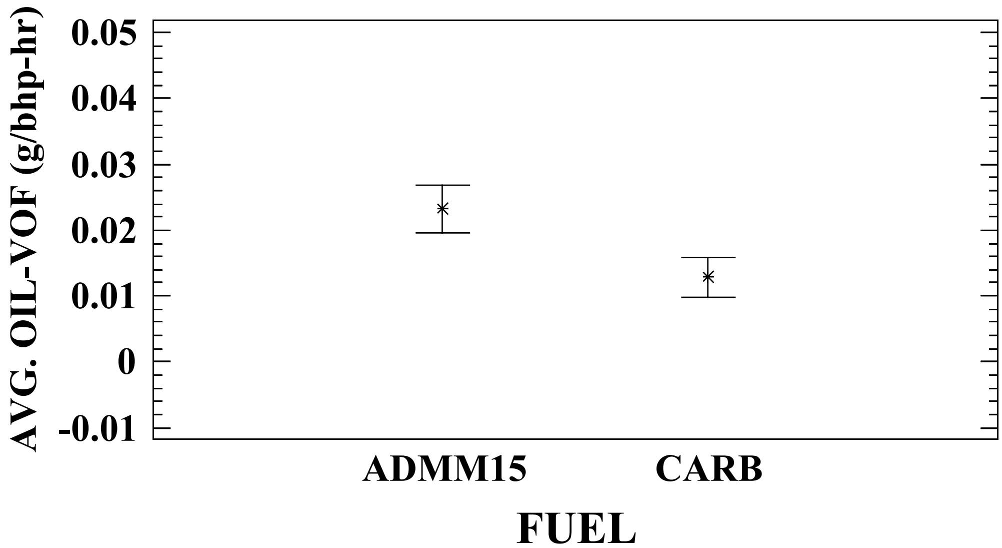
Mode 5 (2600 rpm, 111 ft-lb)
Fuel-VOF

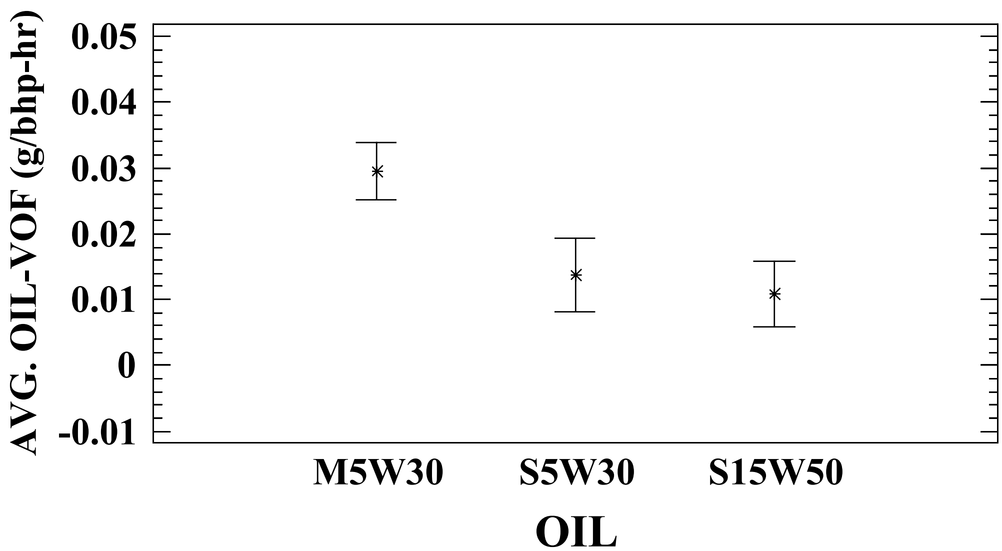


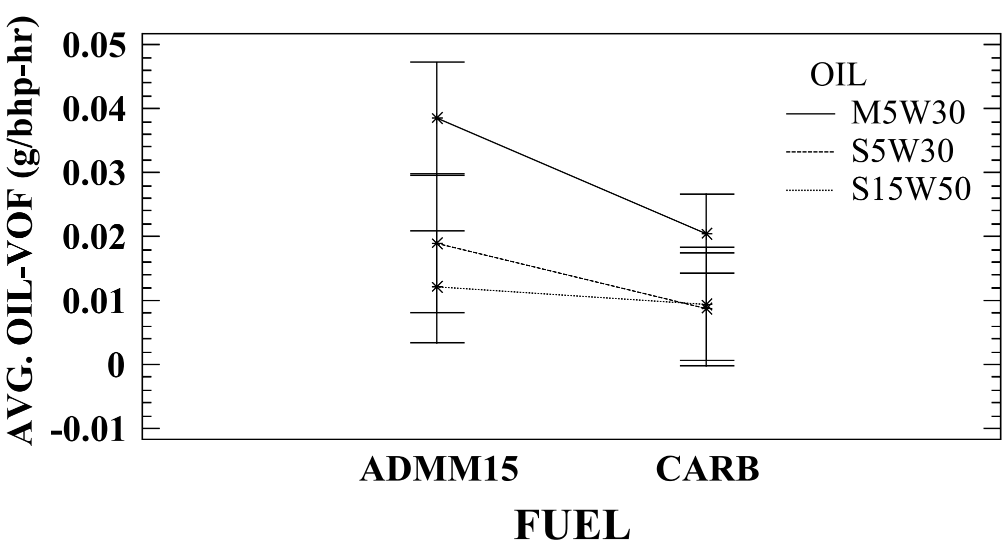




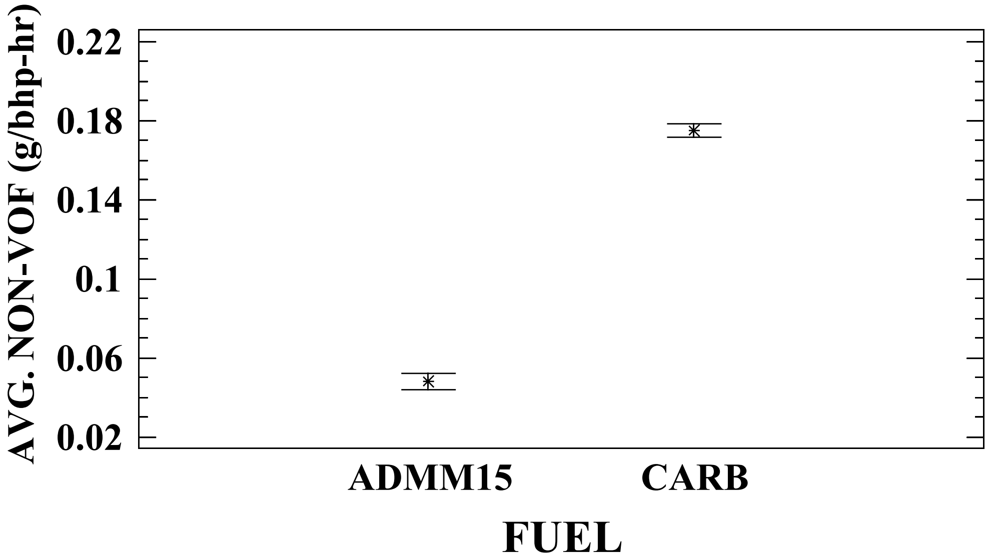
Mode 5 (2600 rpm, 111 ft-lb)
Oil-VOF

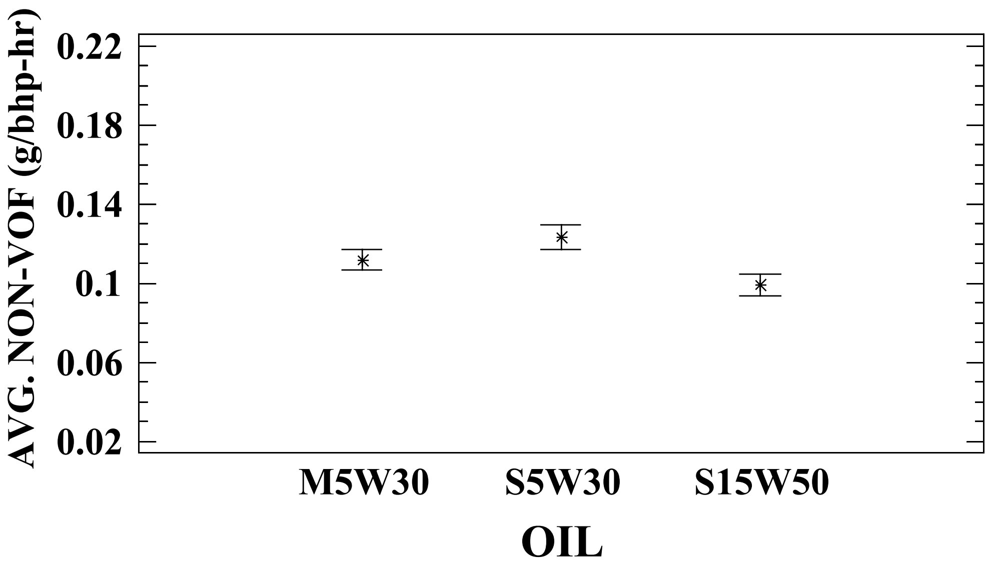


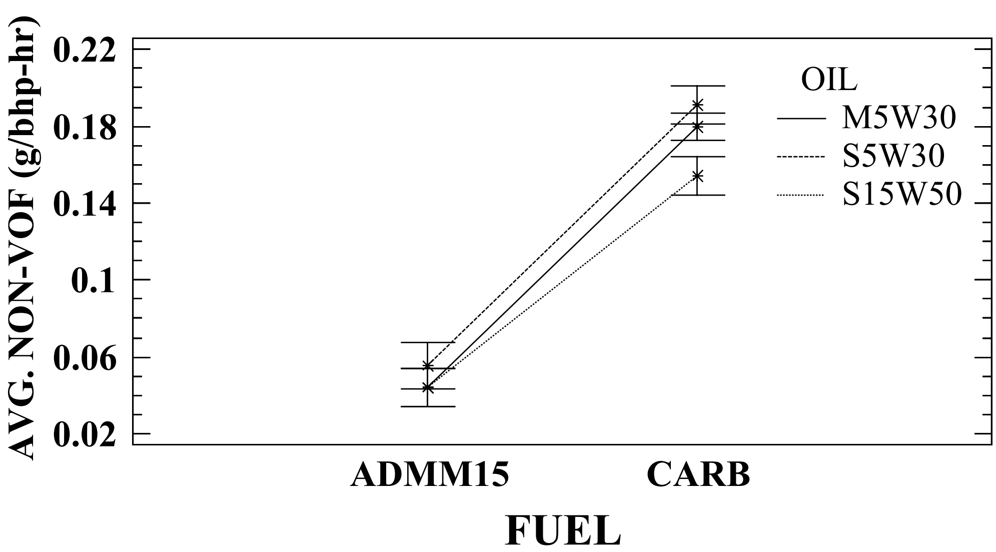




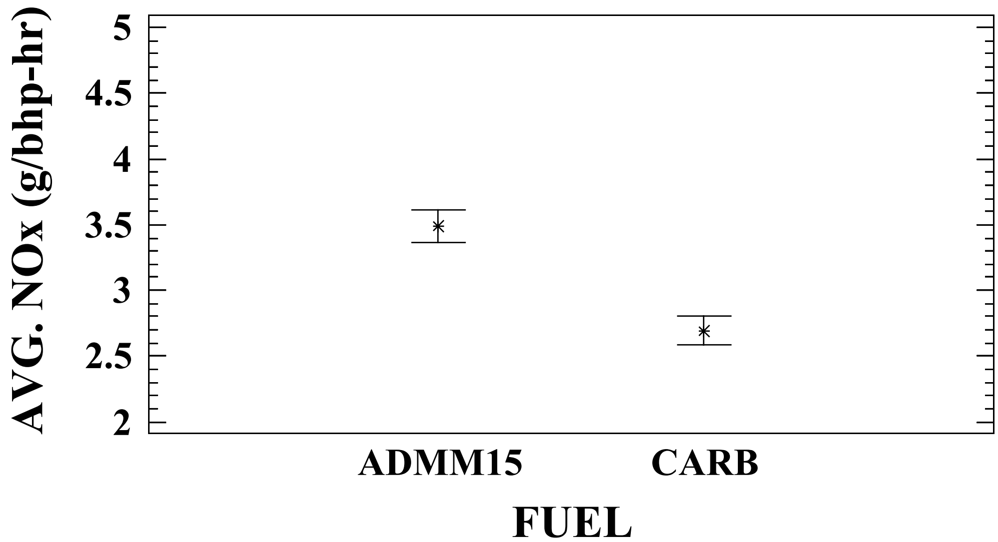
Mode 5 (2600 rpm, 111 ft-lb)
Non-VOF

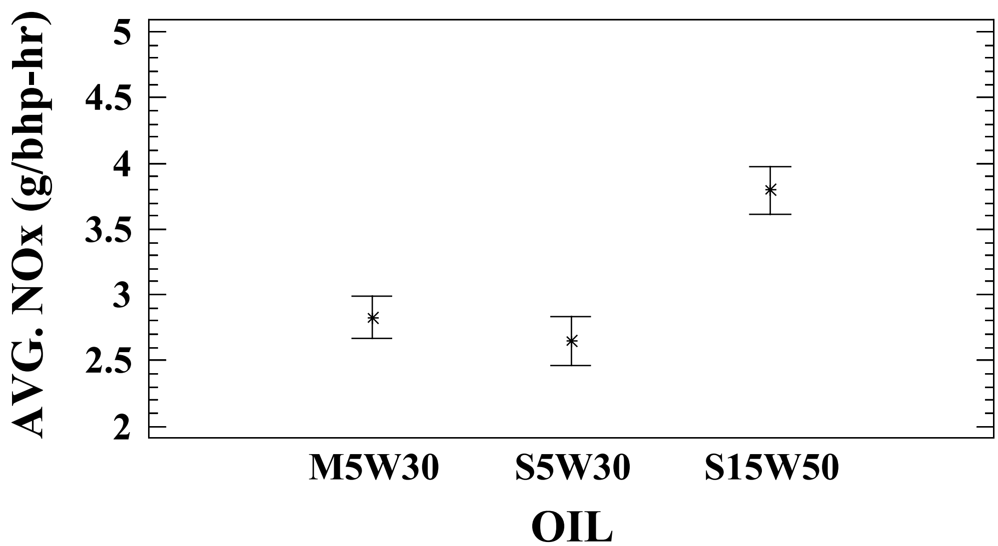


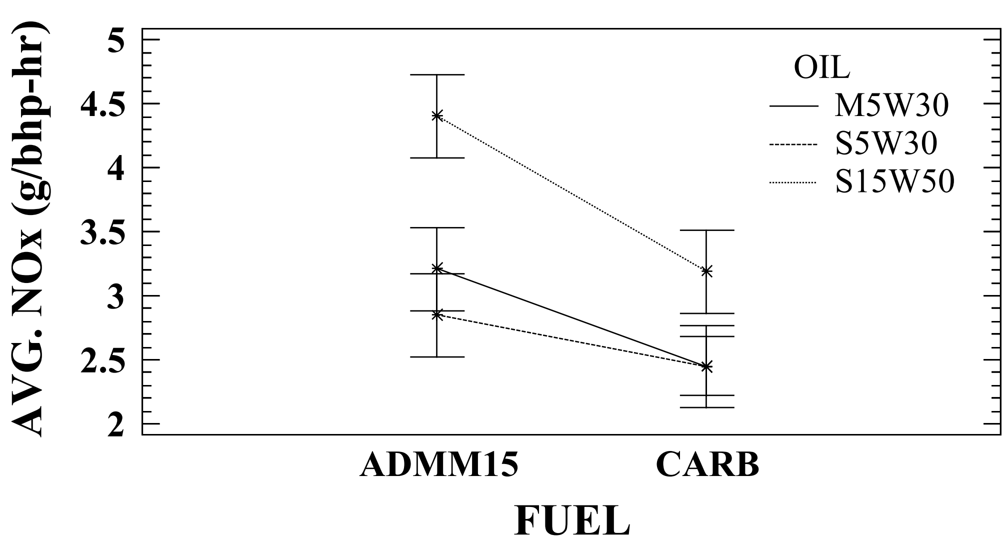




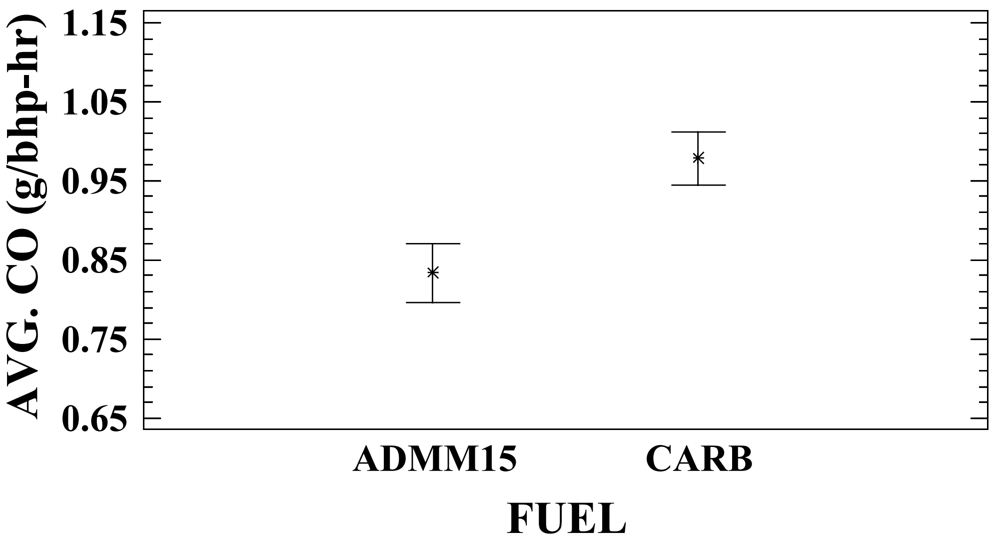
Mode 5 (2600 rpm, 111 ft-lb)
NOx

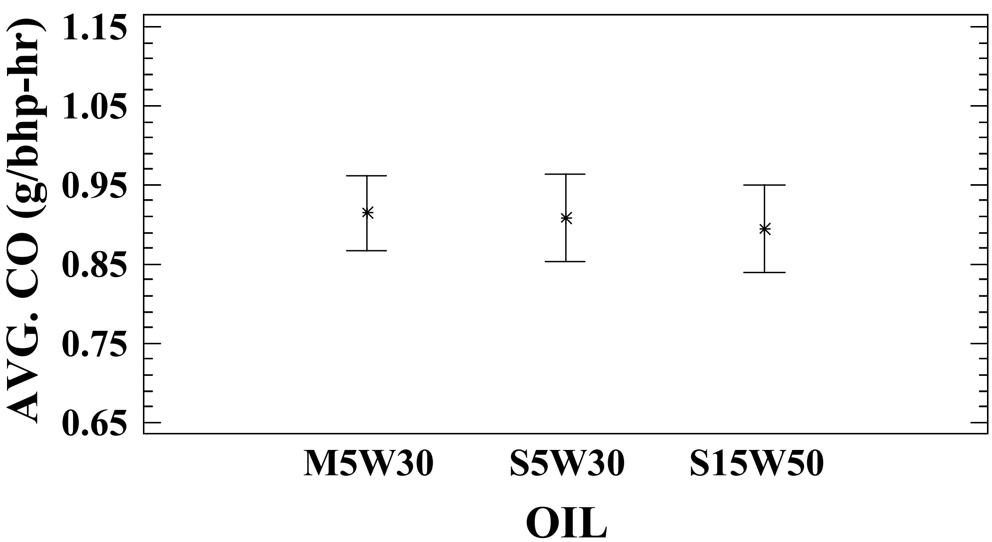


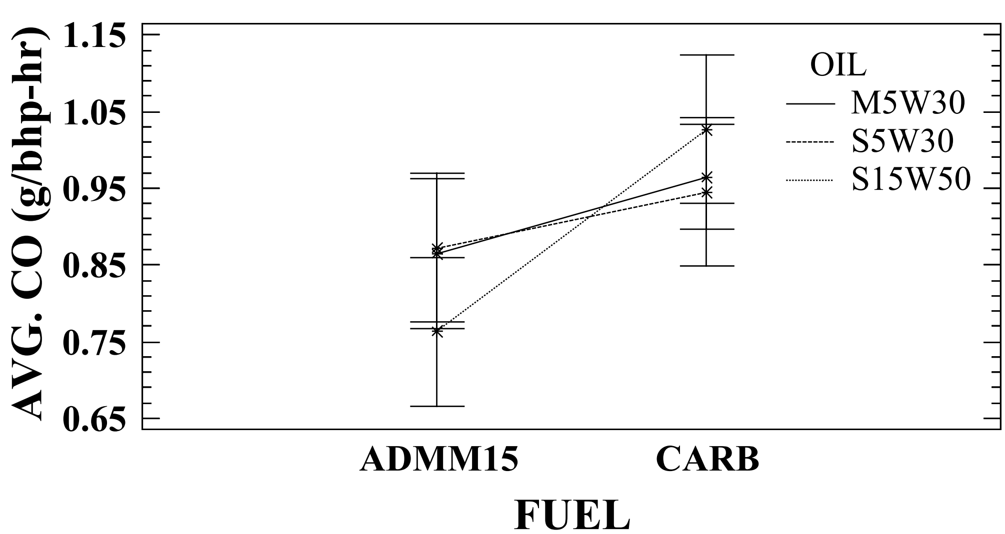




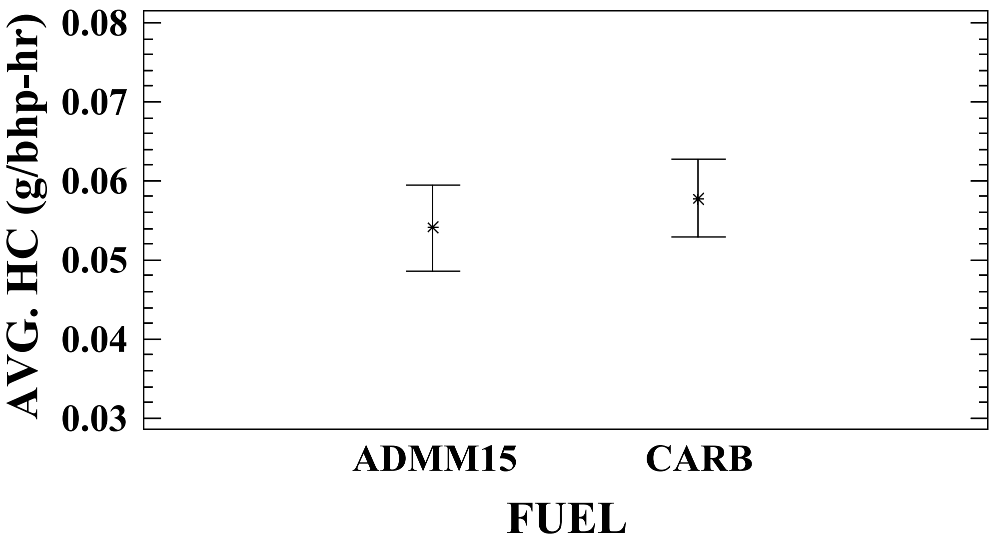
Mode 5 (2600 rpm, 111 ft-lb)
CO

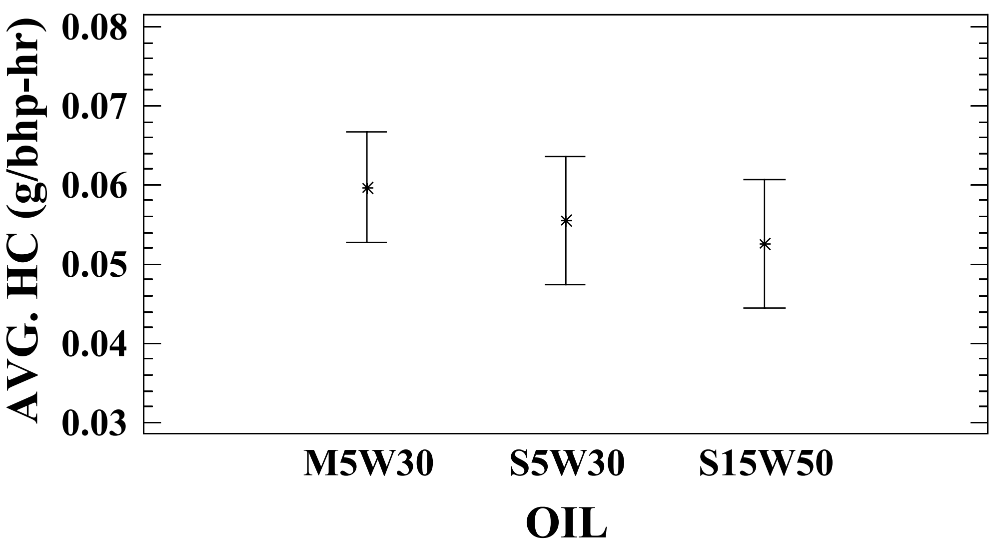


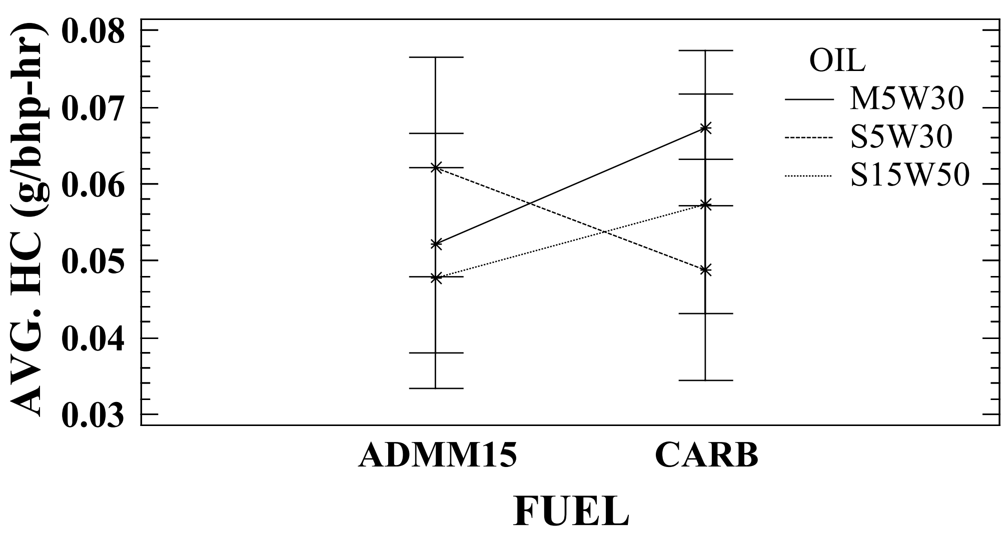




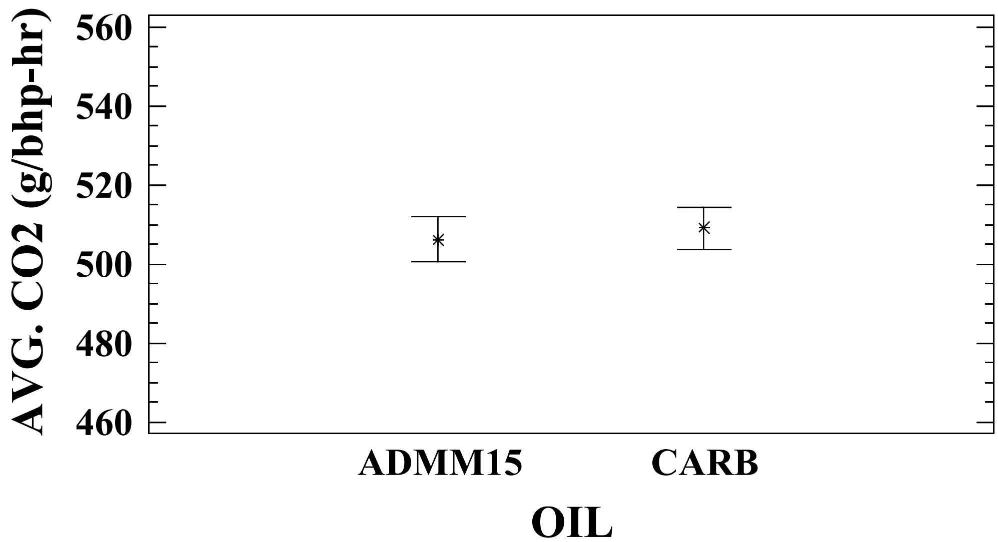
Mode 5 (2600 rpm, 111 ft-lb)
HC

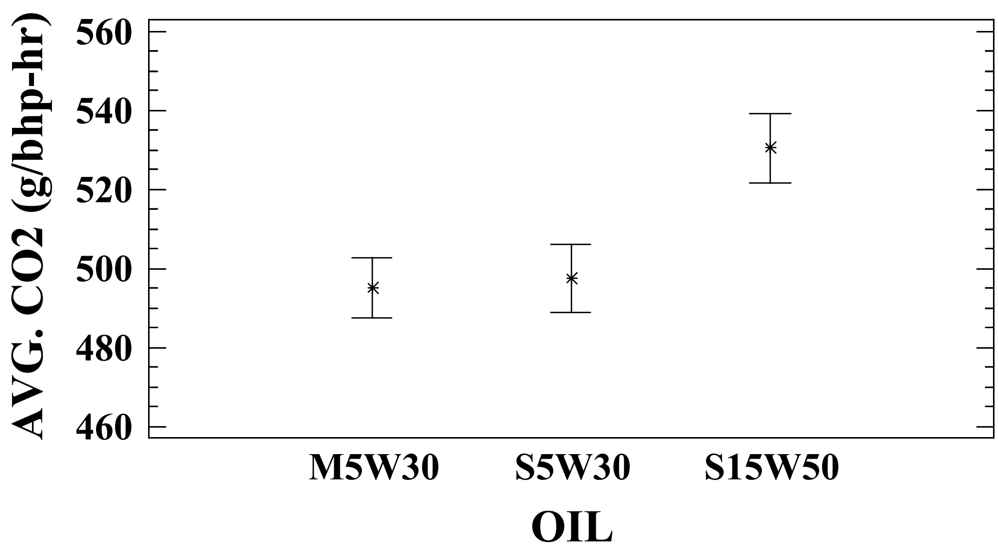


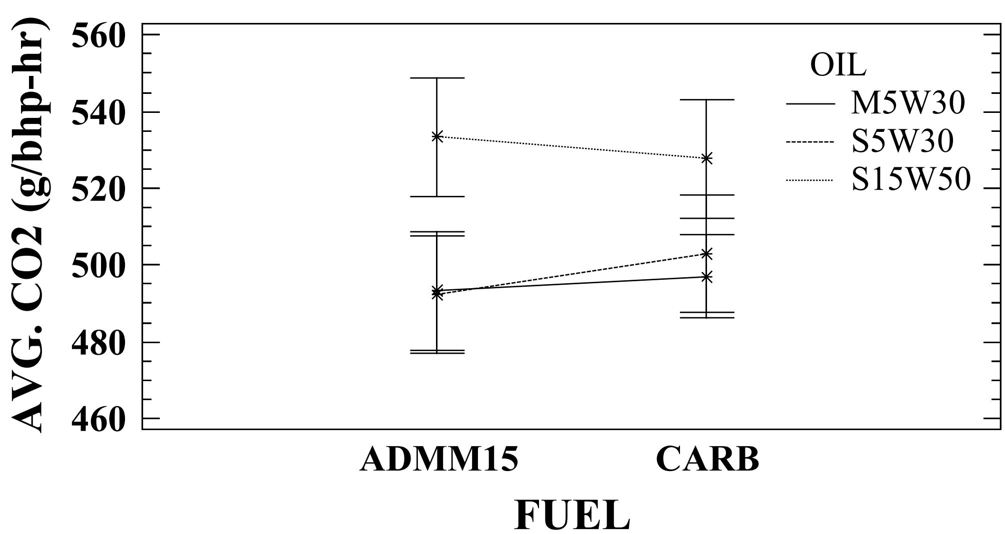




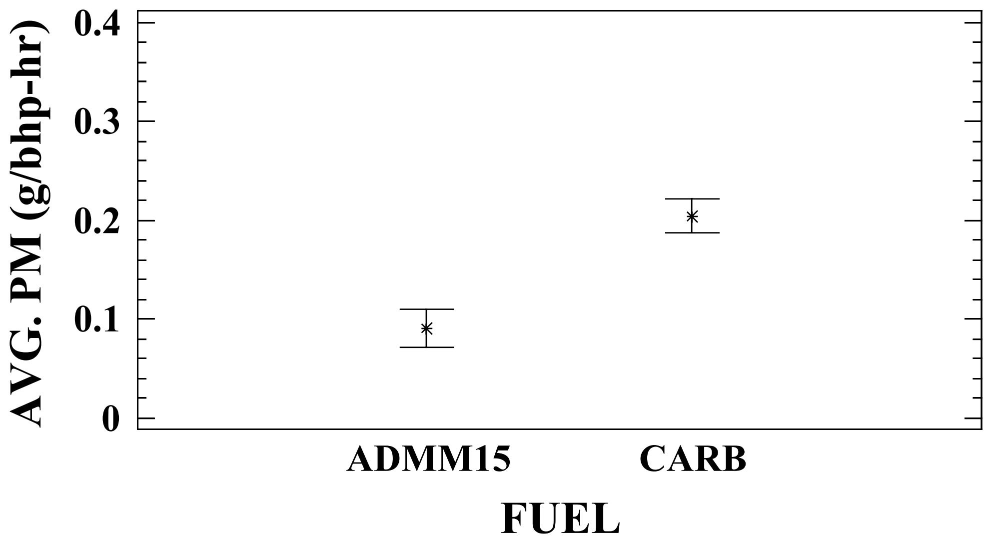
Mode 5 (2600 rpm, 111 ft-lb)
CO2

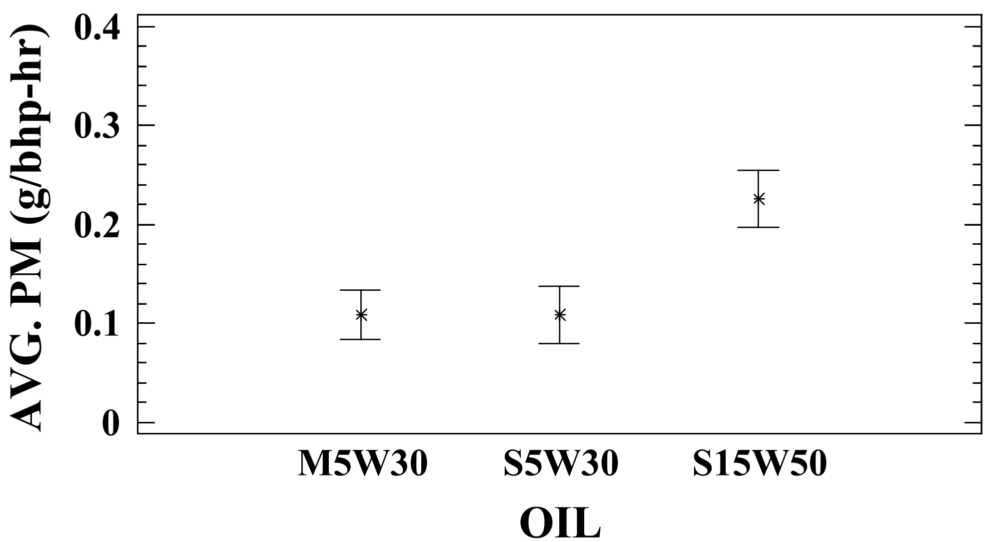


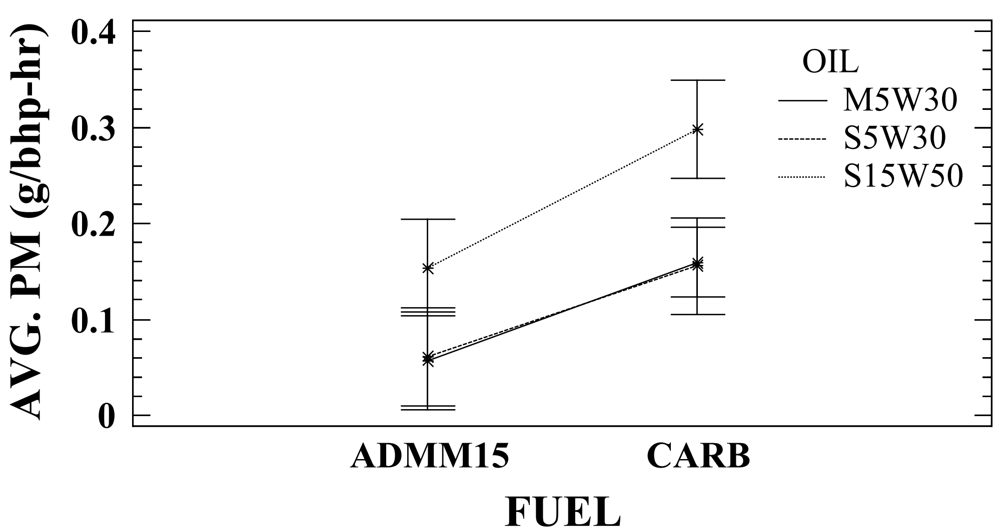




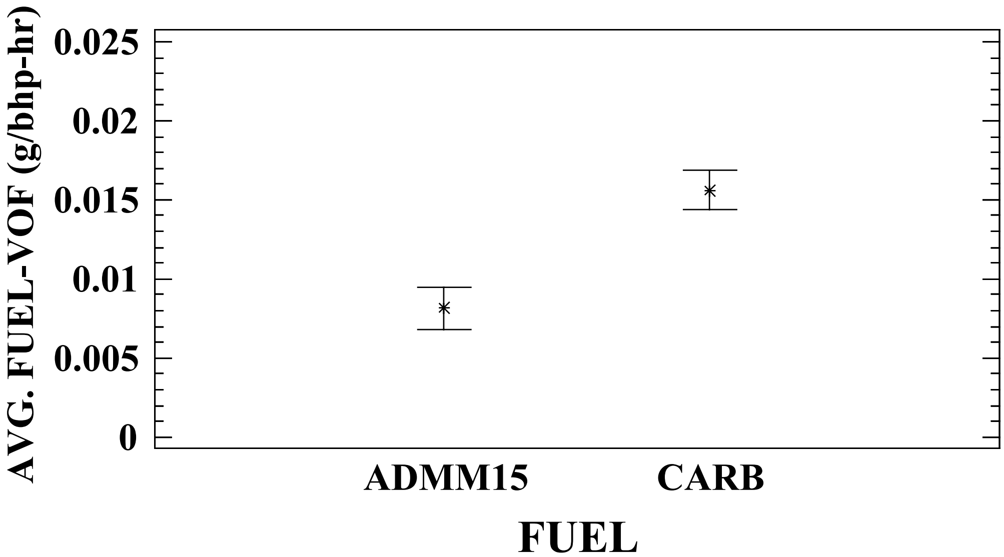
Mode 17 (2600 rpm, 229 ft-lb)
Particulate (PM)

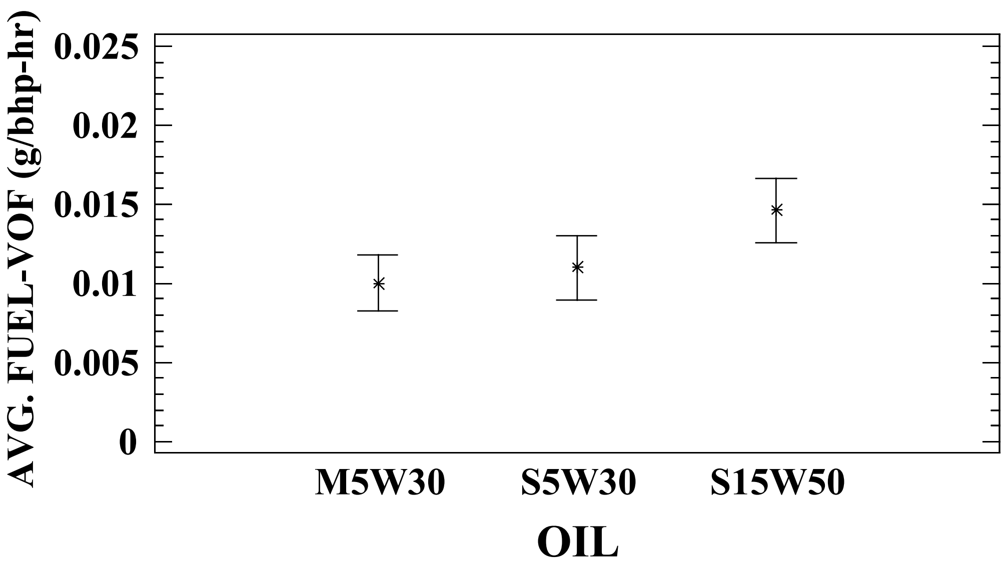


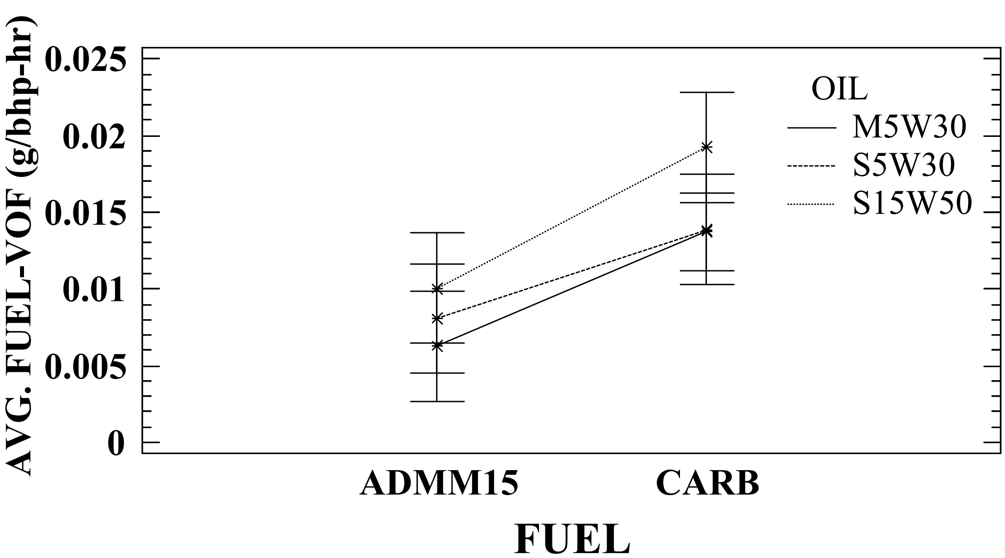




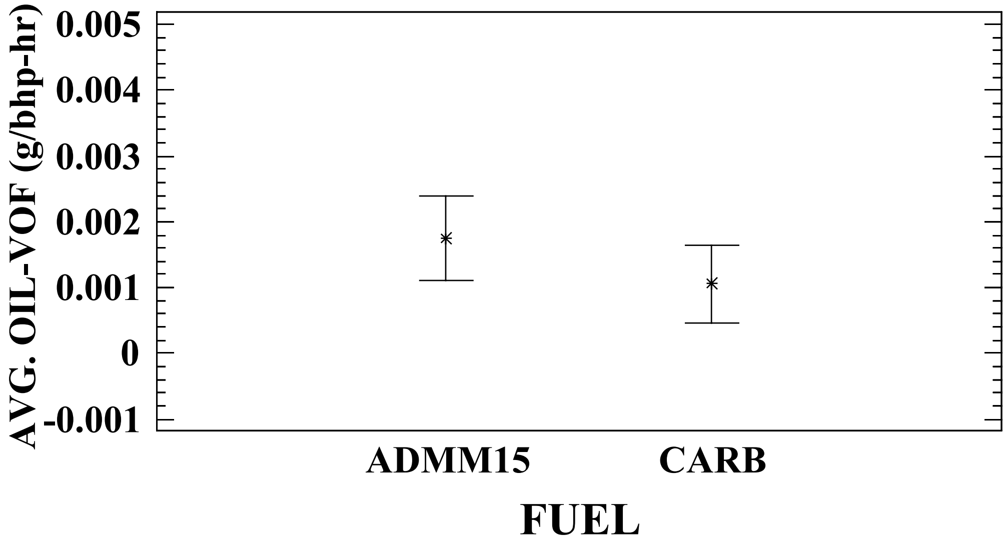
Mode 17 (2600 rpm, 229 ft-lb)
Fuel-VOF

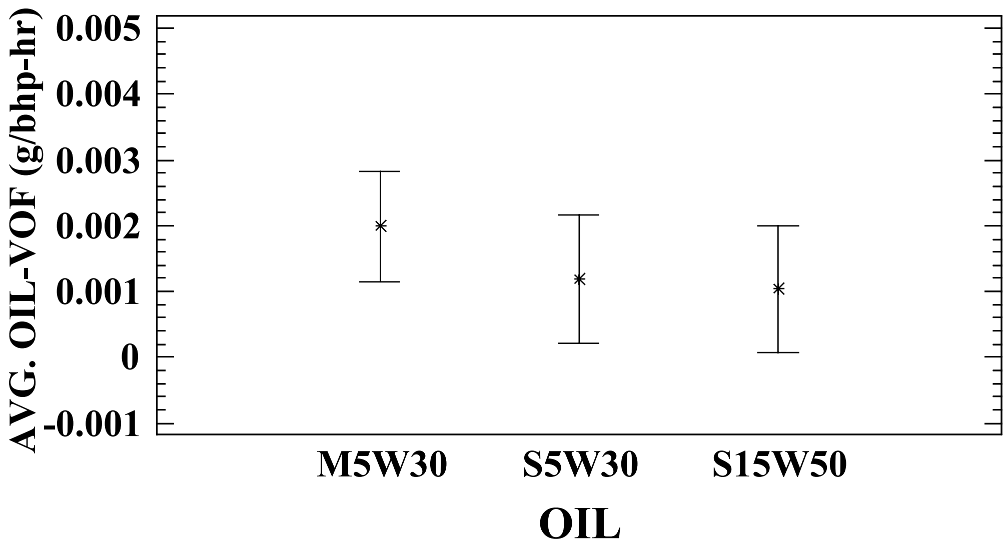


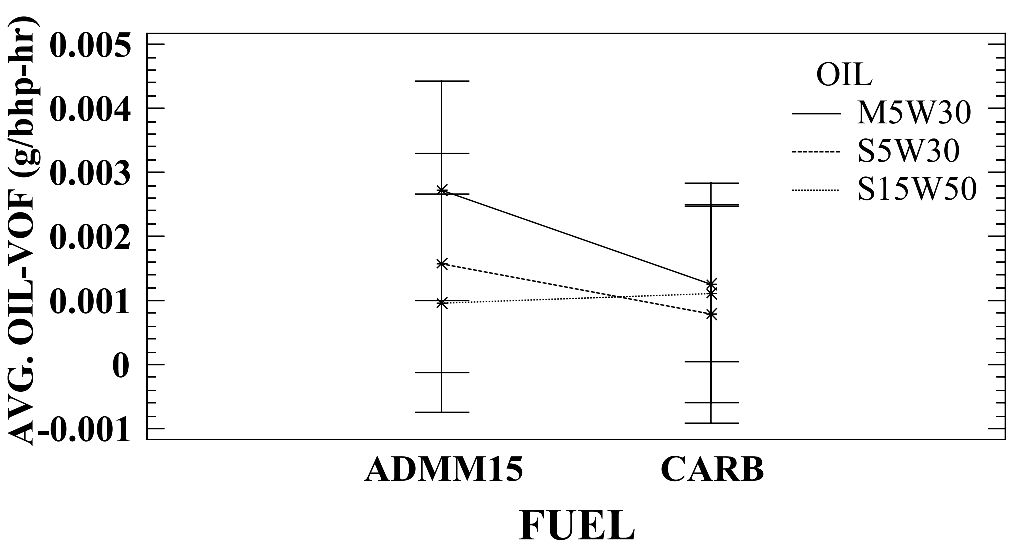




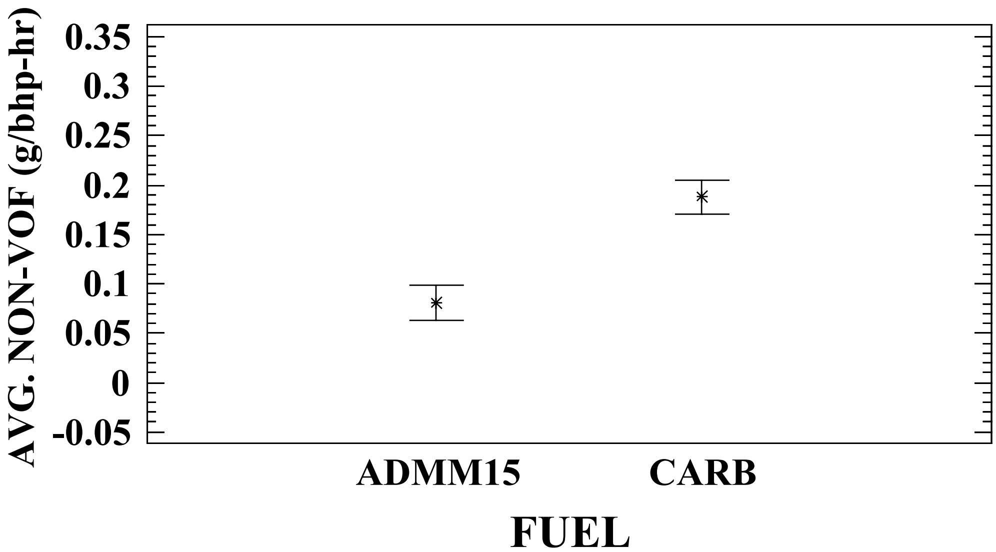
Mode 17 (2600 rpm, 229 ft-lb)
Oil-VOF

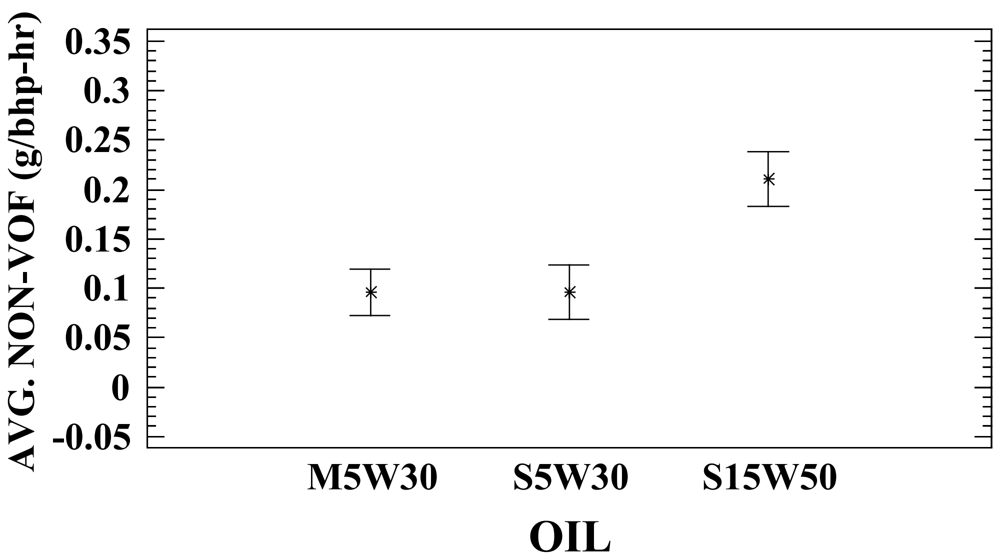


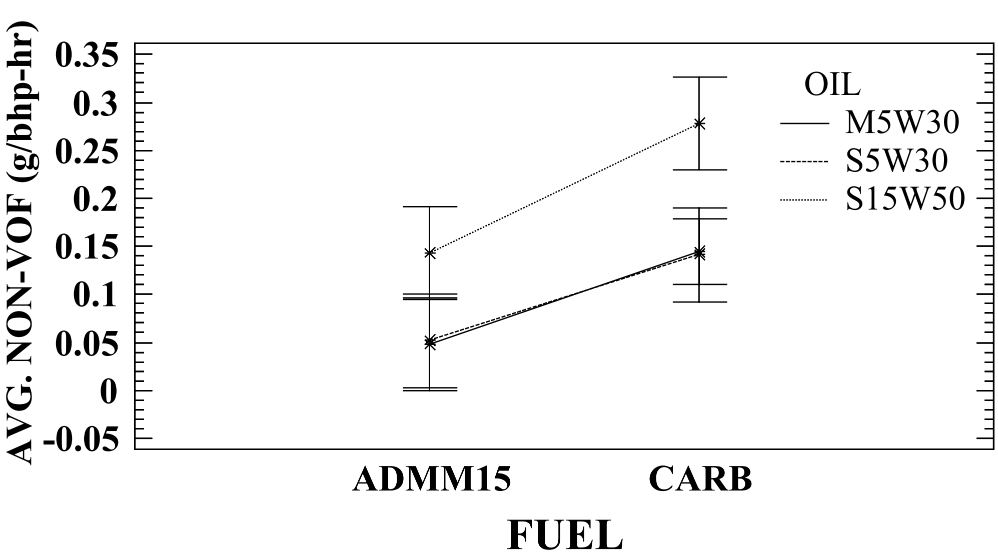




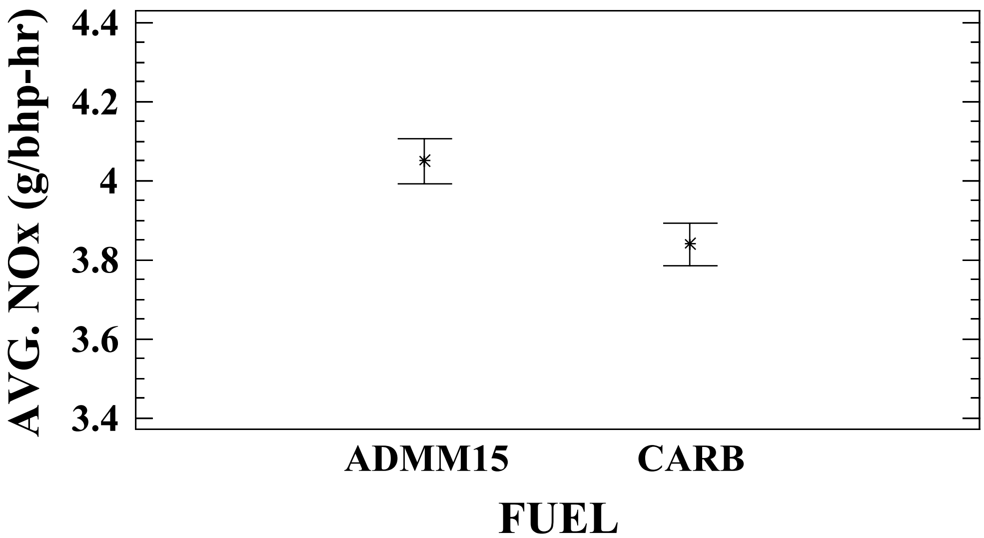
Mode 17 (2600 rpm, 229 ft-lb)
Non-VOF

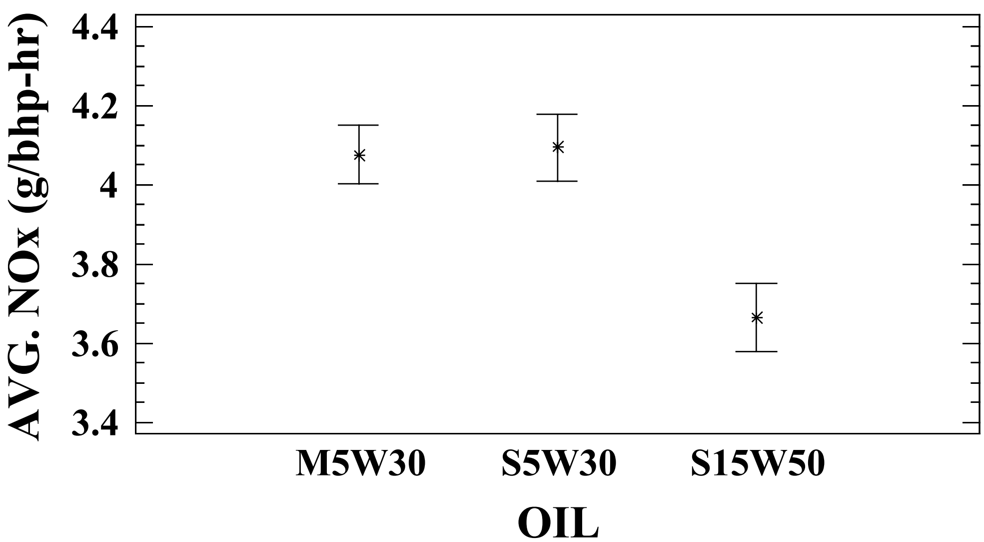


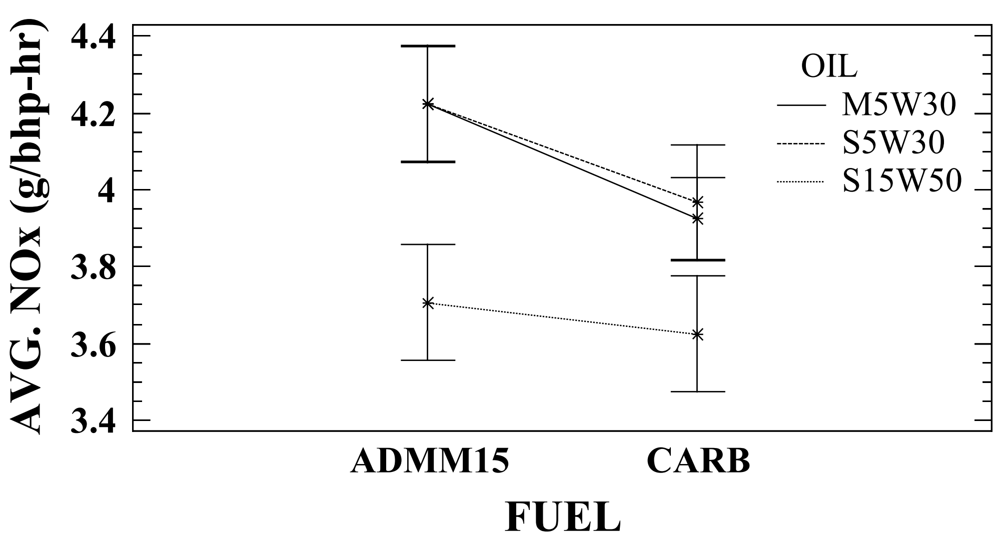




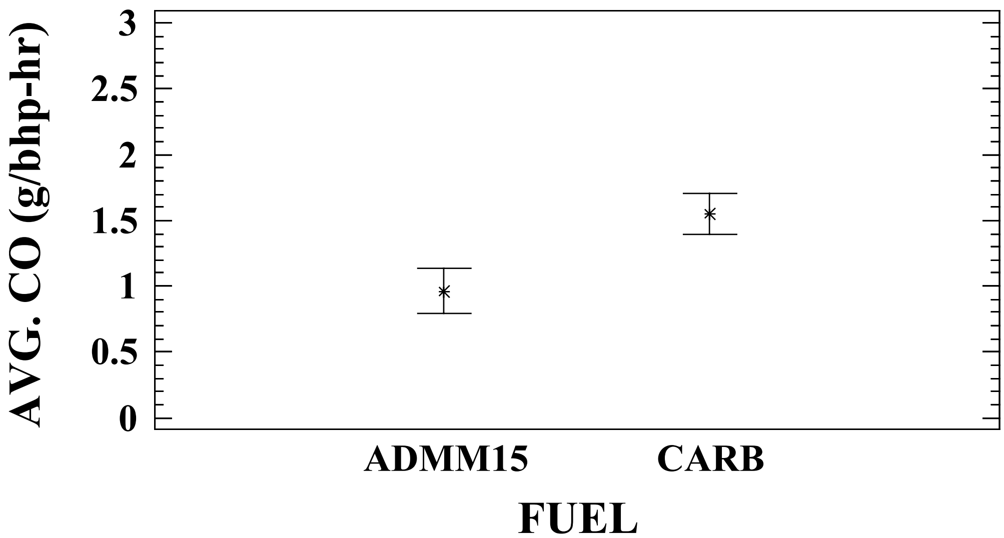
Mode 17 (2600 rpm, 229 ft-lb)
NOx

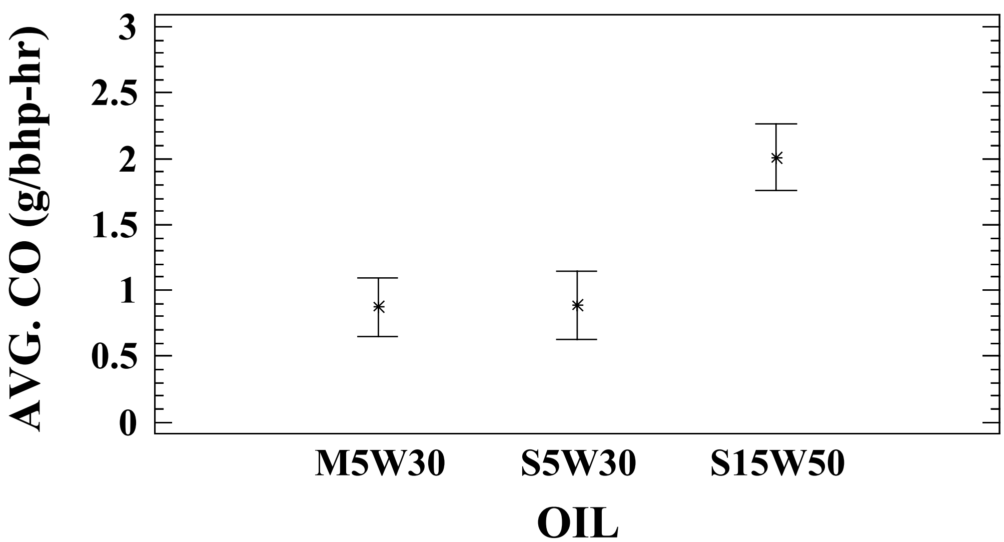


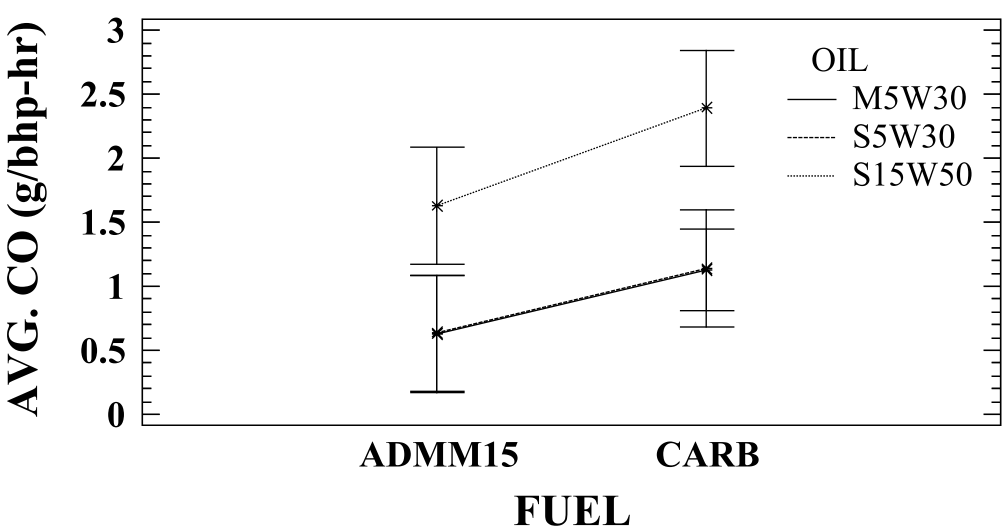




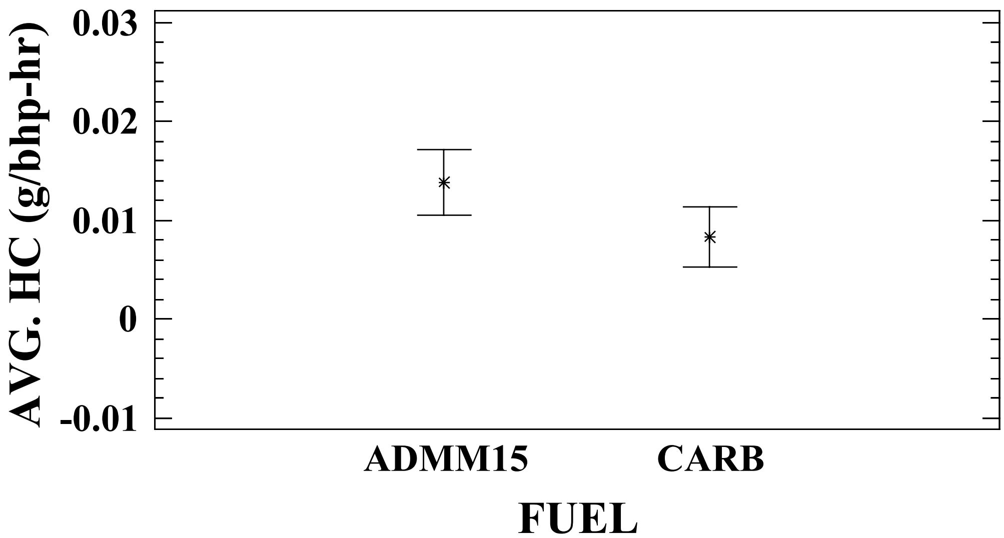
Mode 17 (2600 rpm, 229 ft-lb)
CO

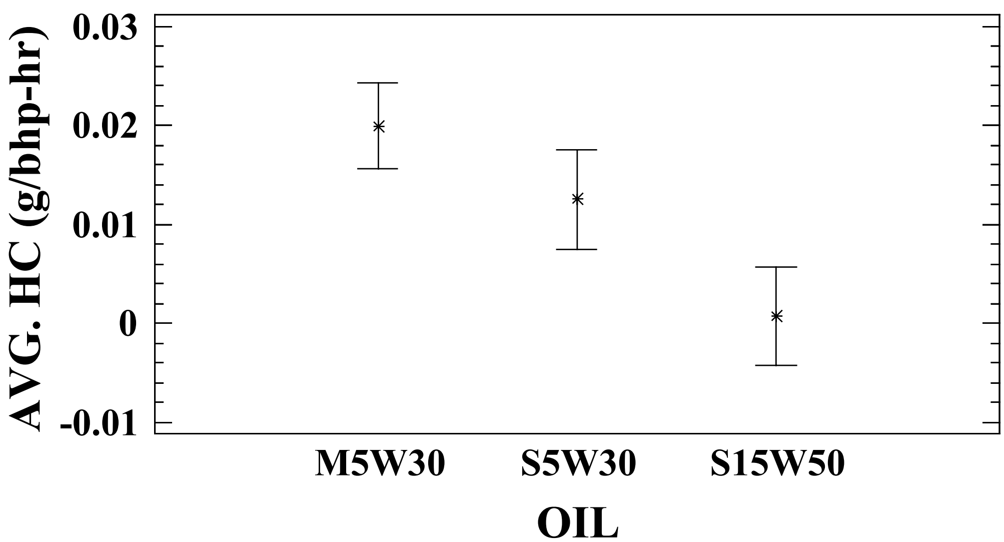


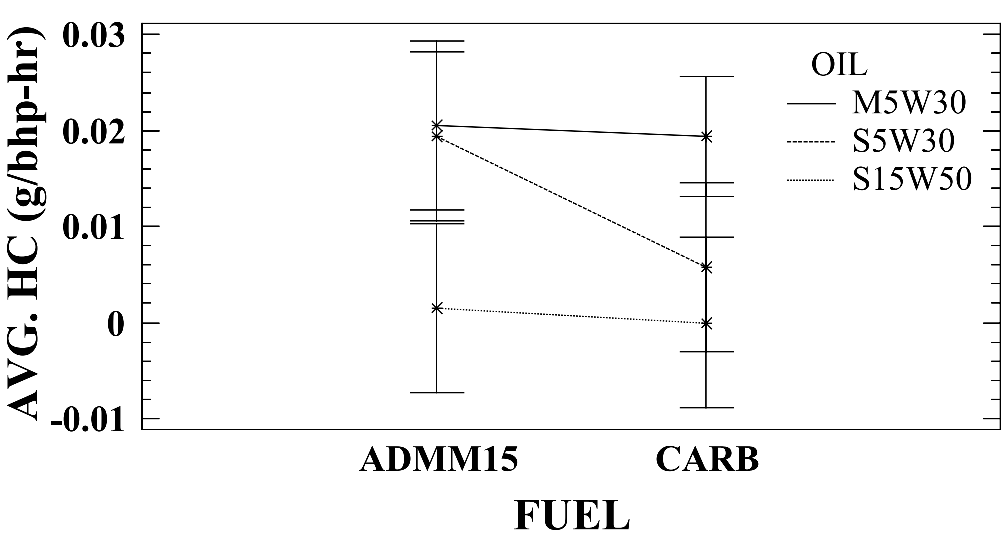




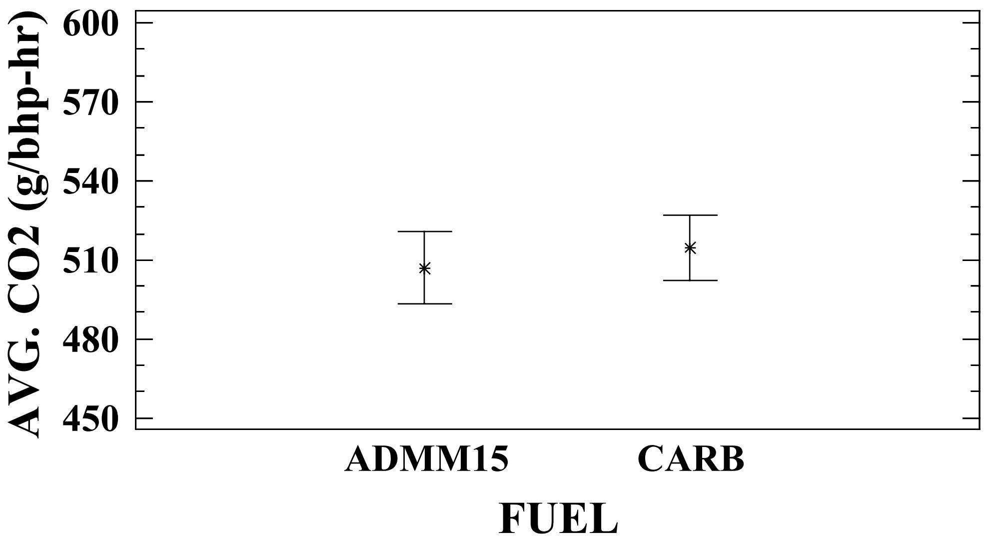
Mode 17 (2600 rpm, 229 ft-lb)
HC

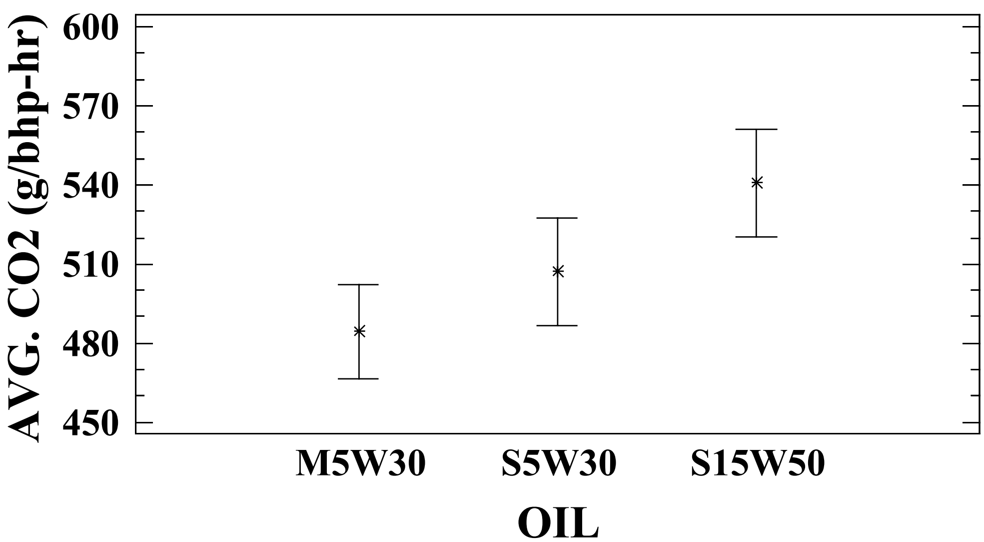


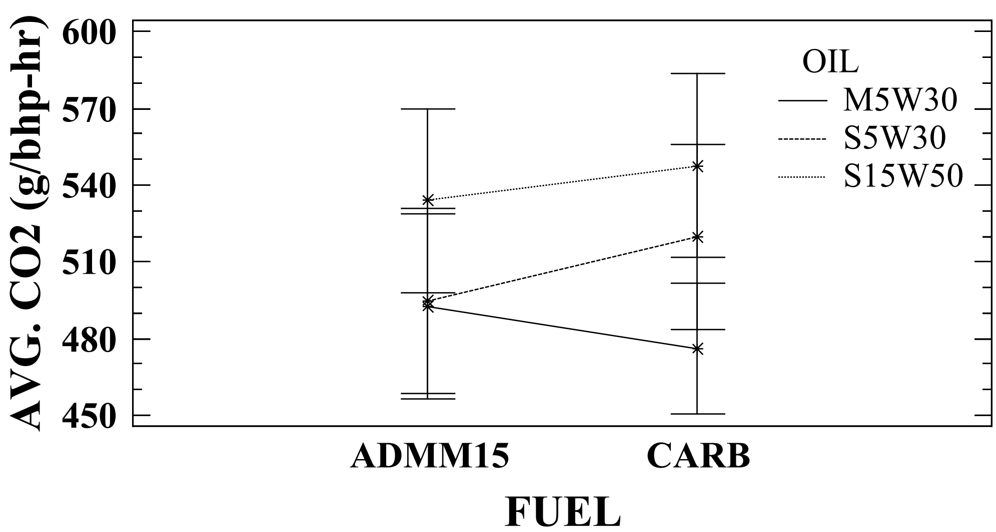




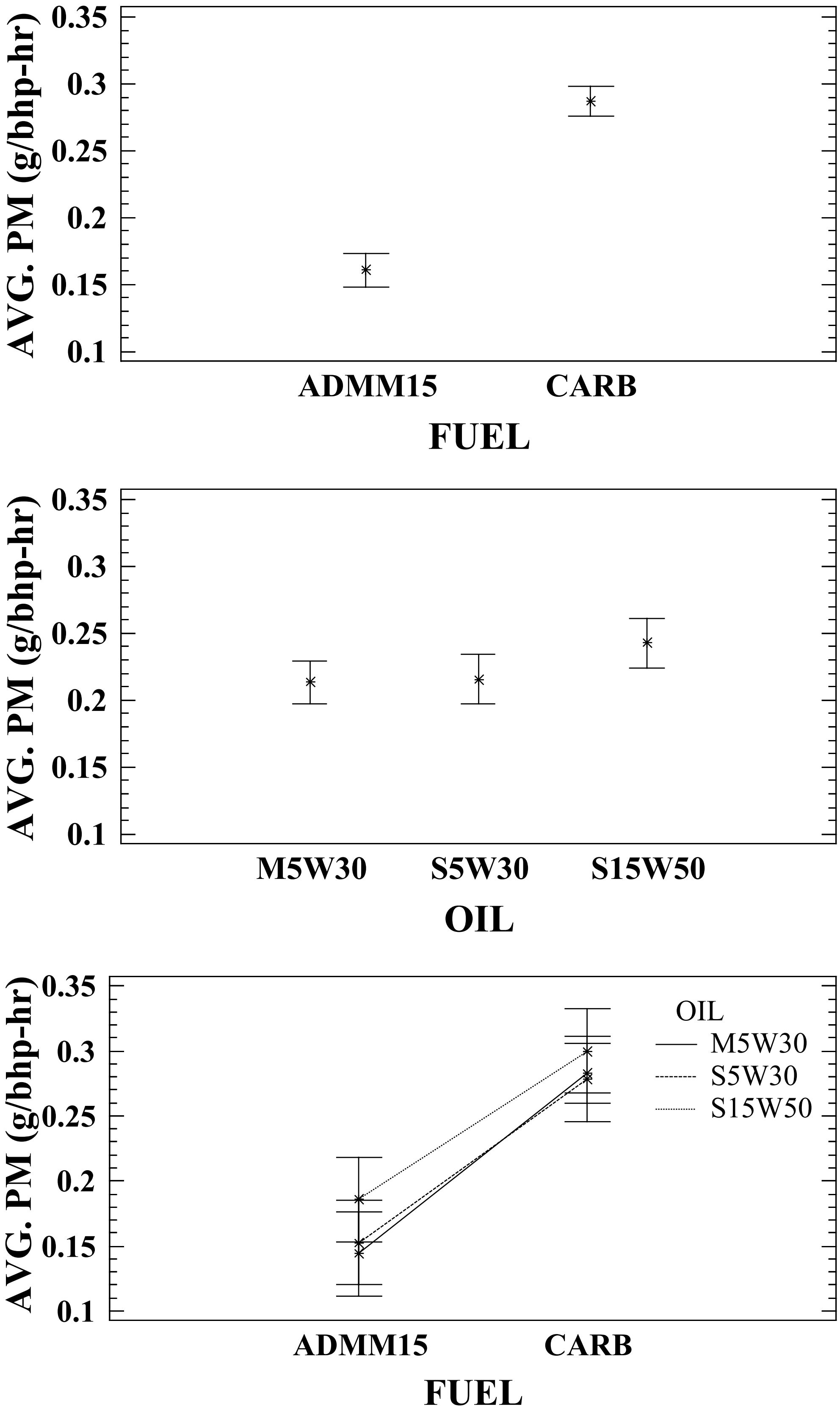
Mode 17 (2600 rpm, 229 ft-lb)
CO2



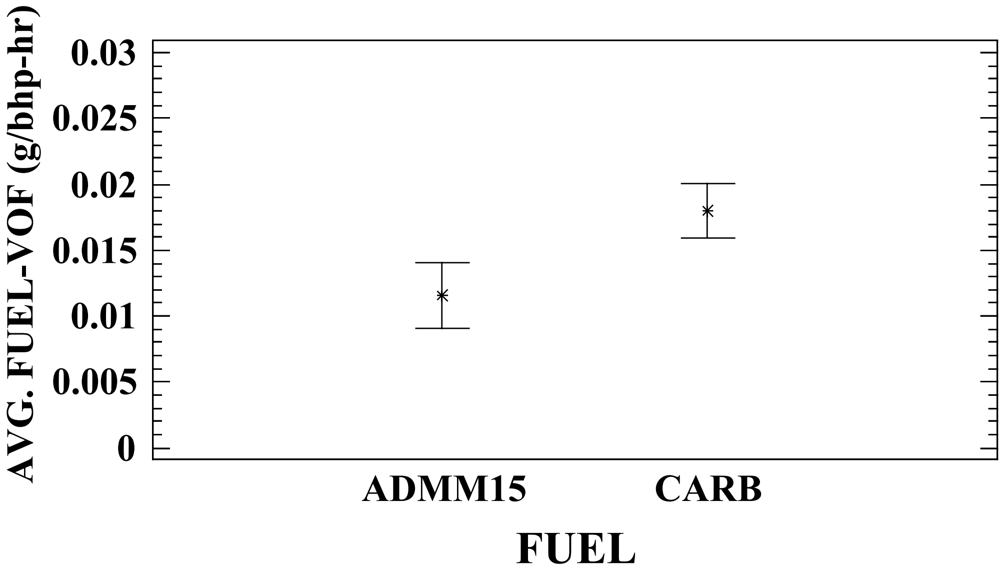


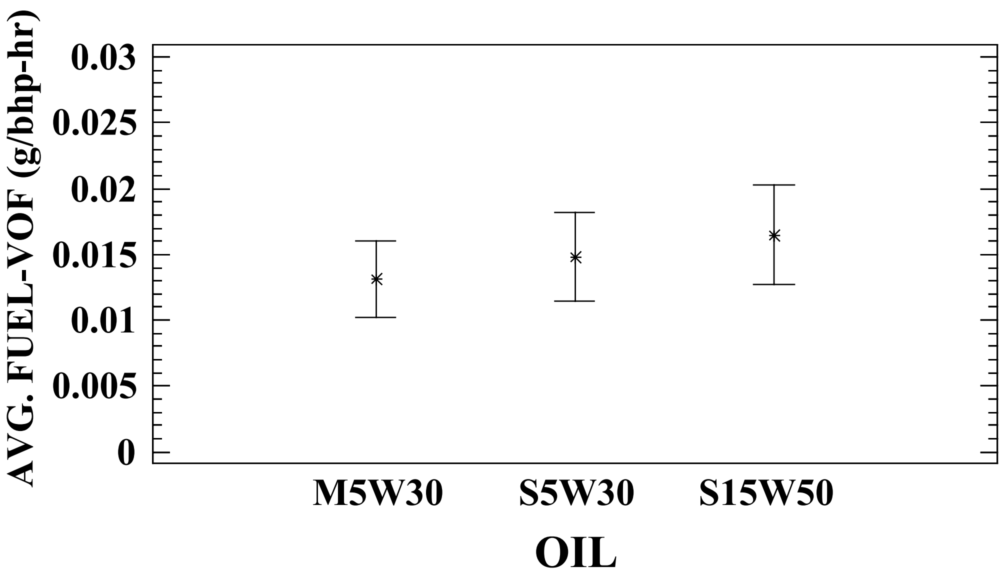


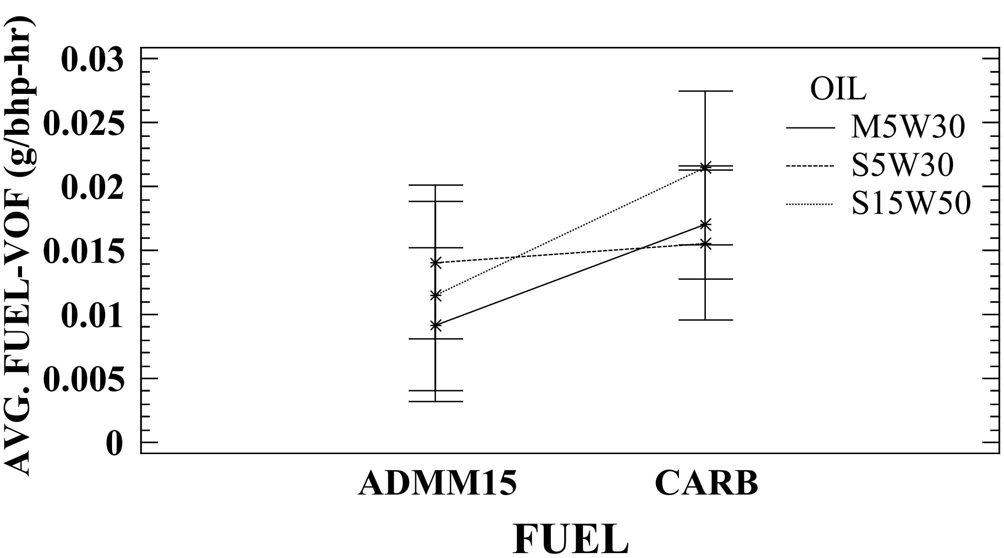
Mode 14 (4200 rpm, 158 ft-lb)
Particulate (PM)



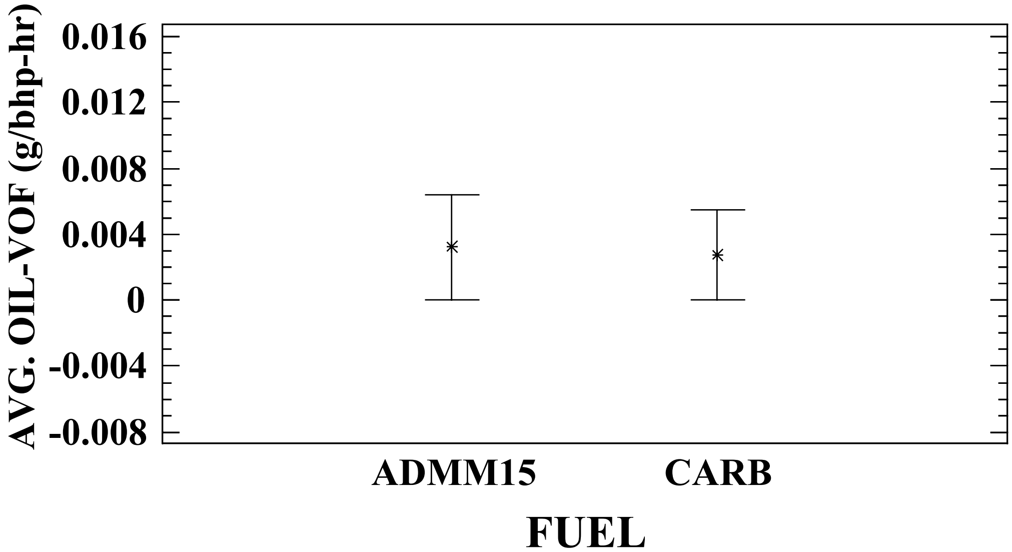
Mode 14 (4200 rpm, 158 ft-lb)
Fuel-VOF

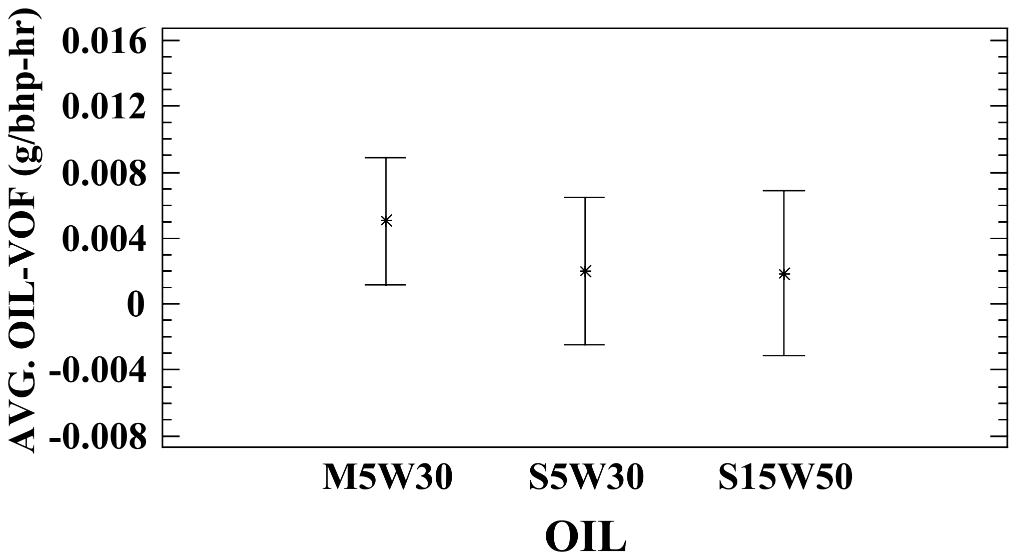


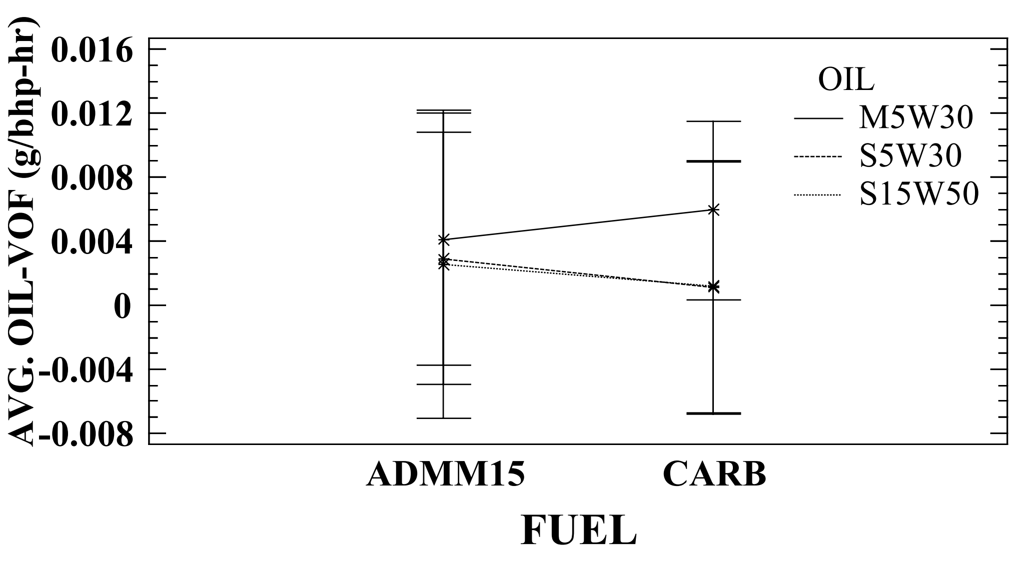




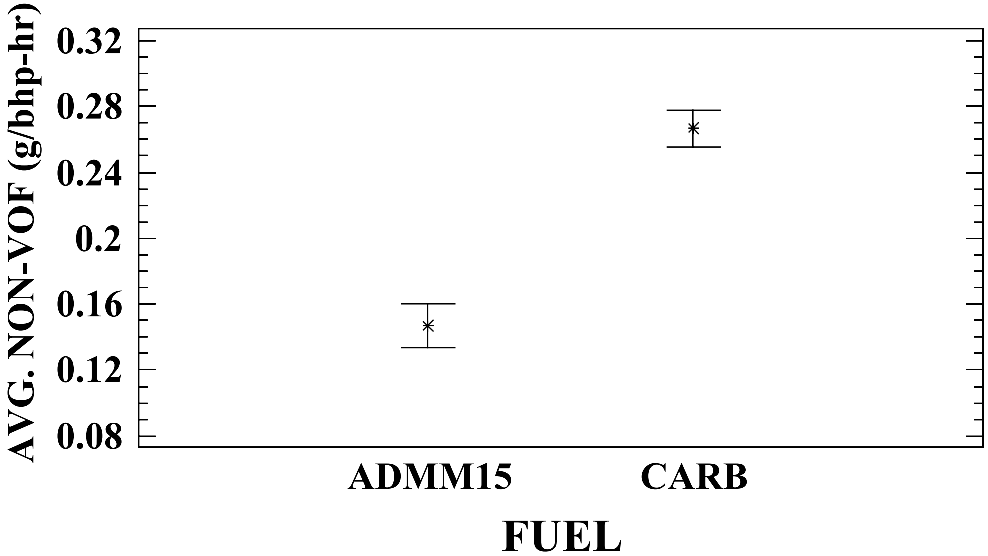
Mode 14 (4200 rpm, 158 ft-lb)
Oil-VOF

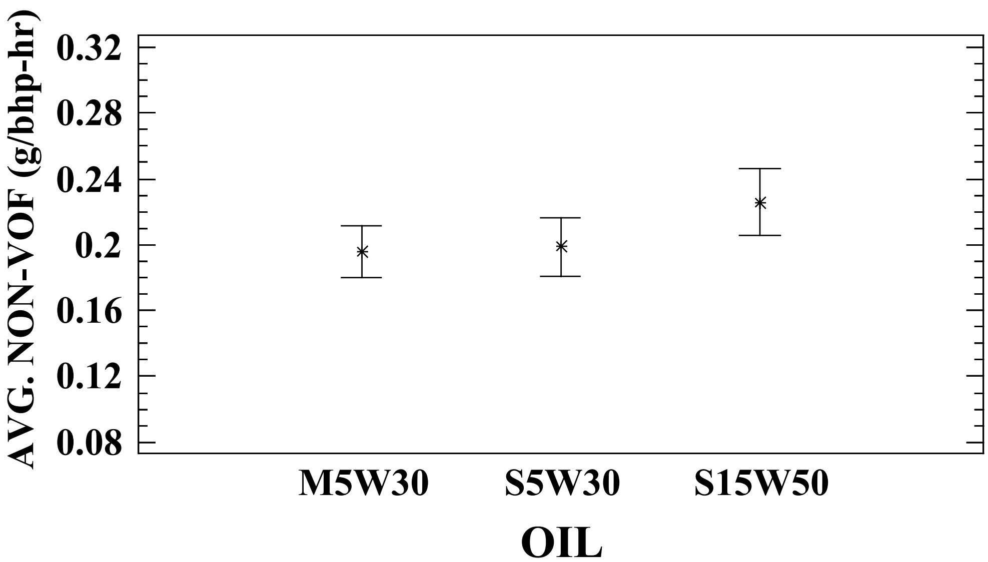


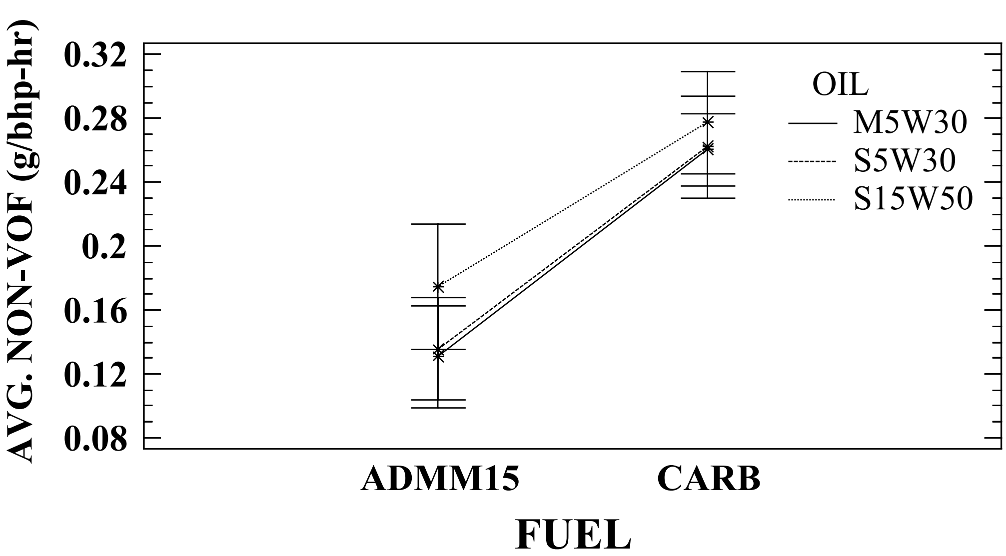




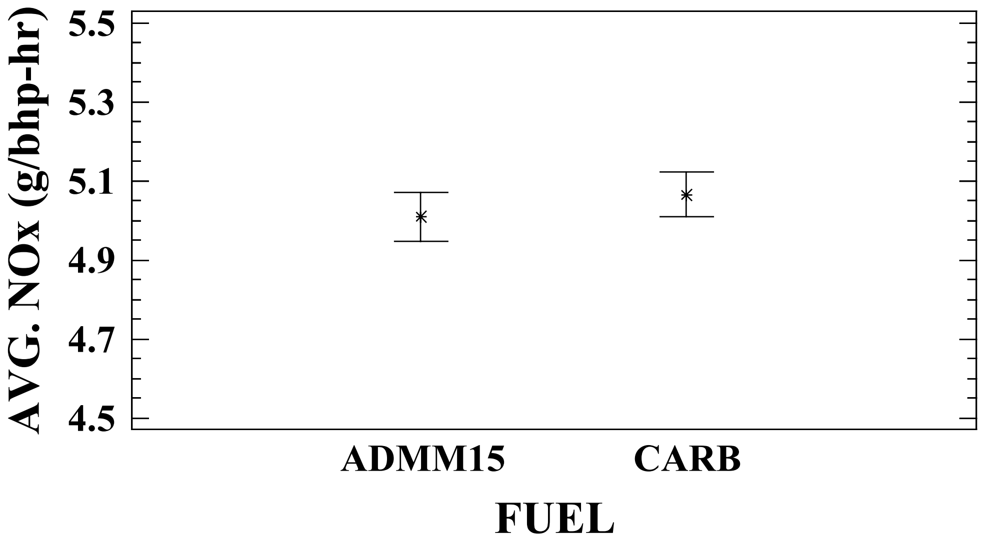
Mode 14 (4200 rpm, 158 ft-lb)
Non-VOF

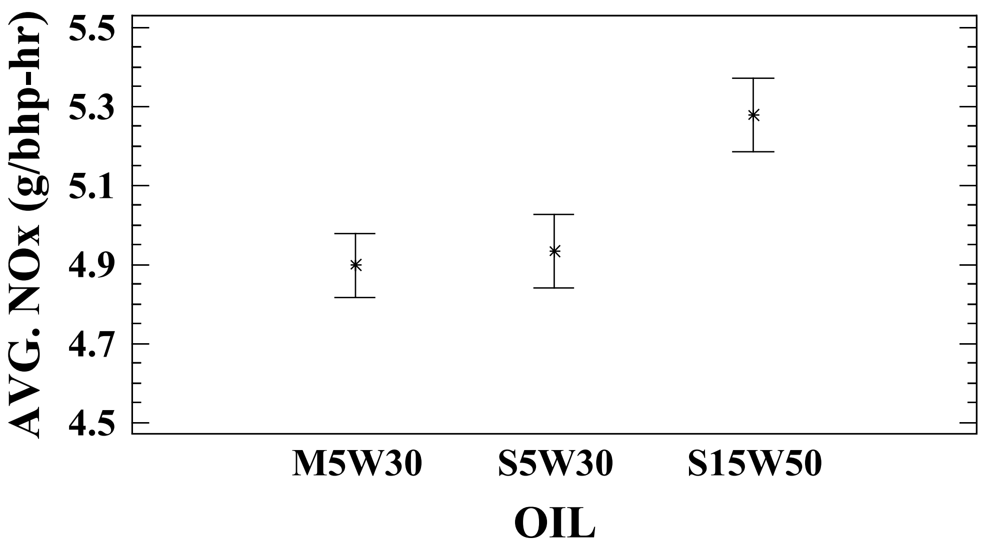


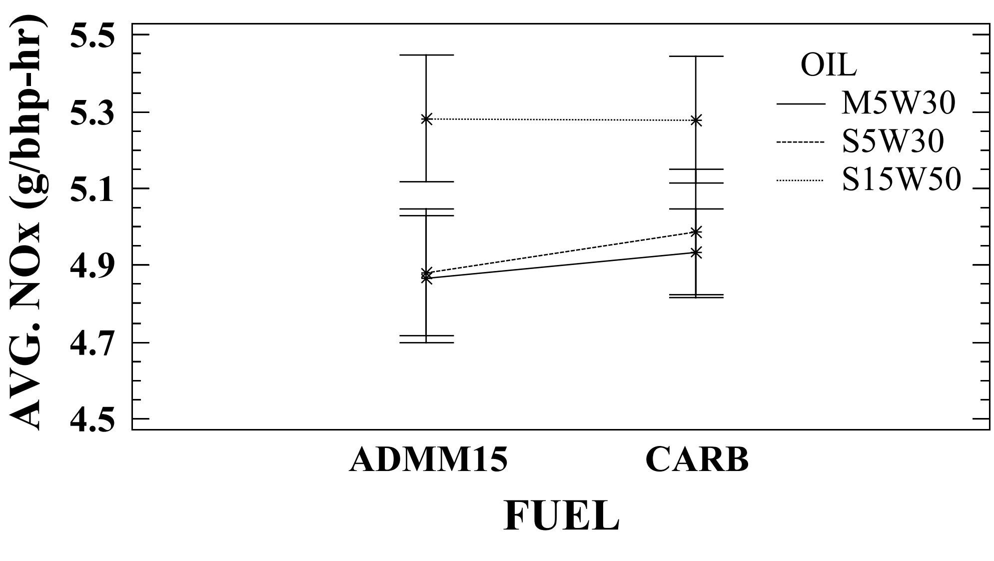




Mode 14 (4200 rpm, 158 ft-lb)
NOx

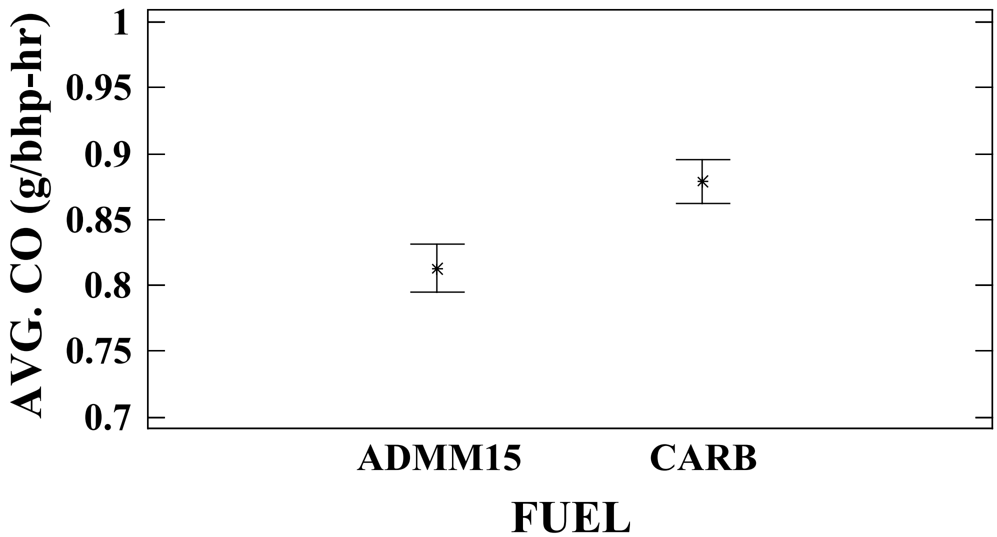


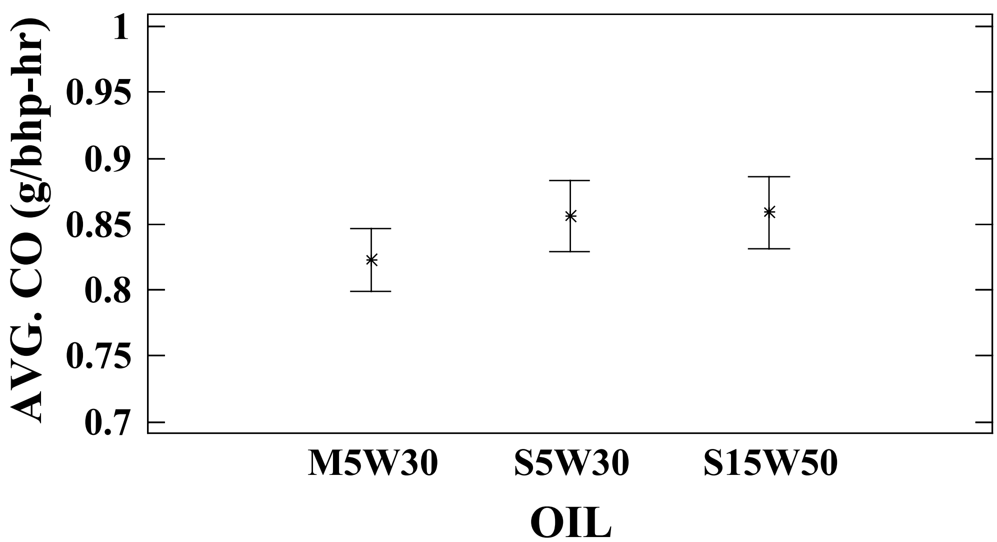


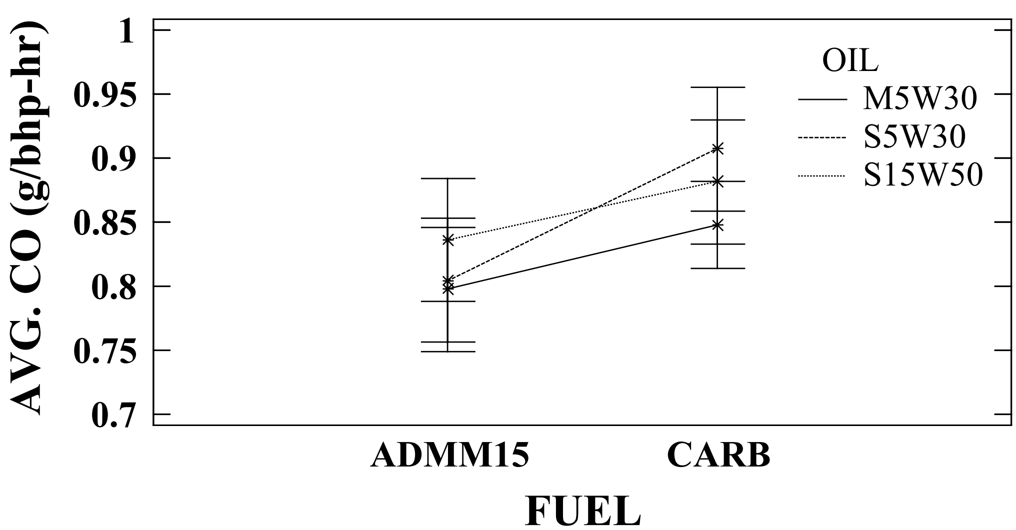


Mode 14 (4200 rpm, 158 ft-lb)

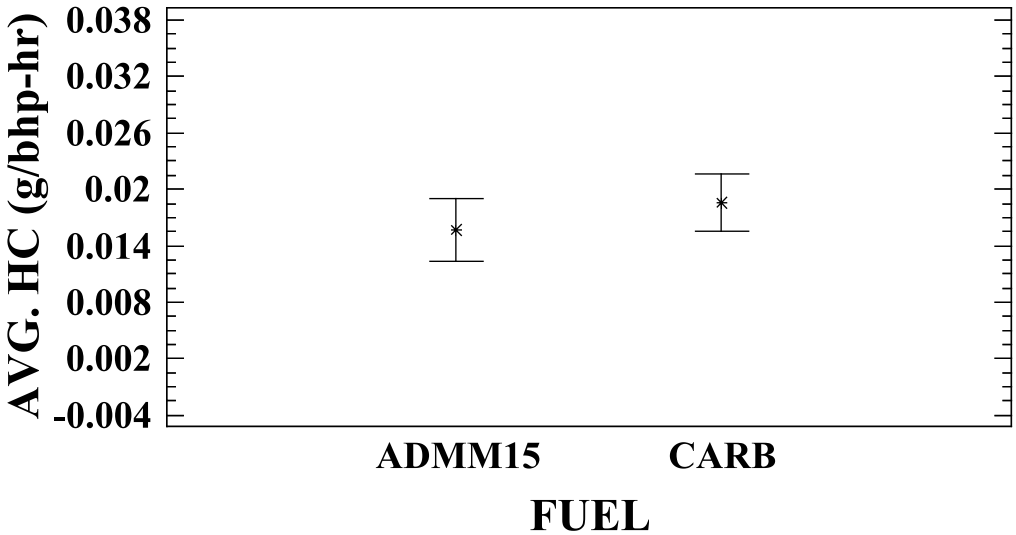
CO

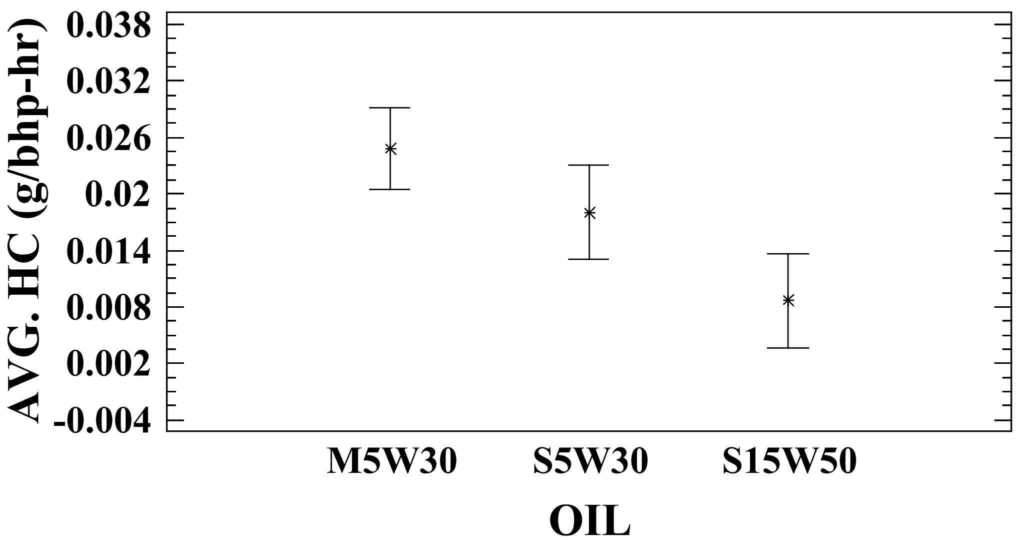


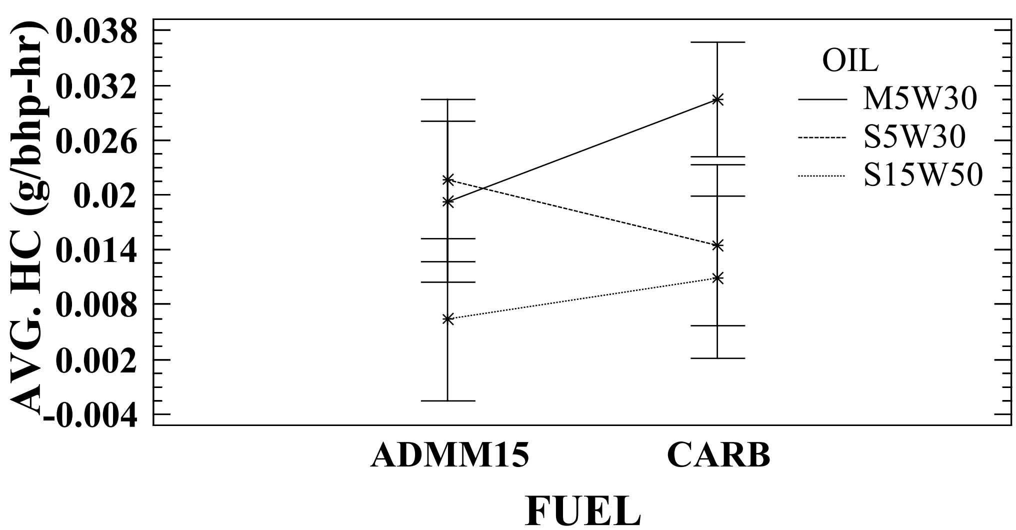




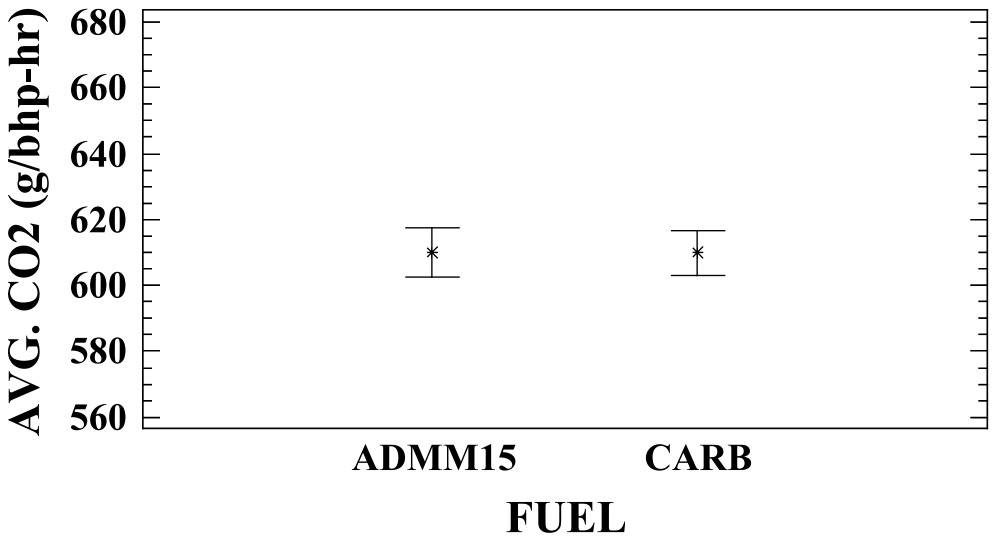
Mode 14 (4200 rpm, 158 ft-lb)
HC

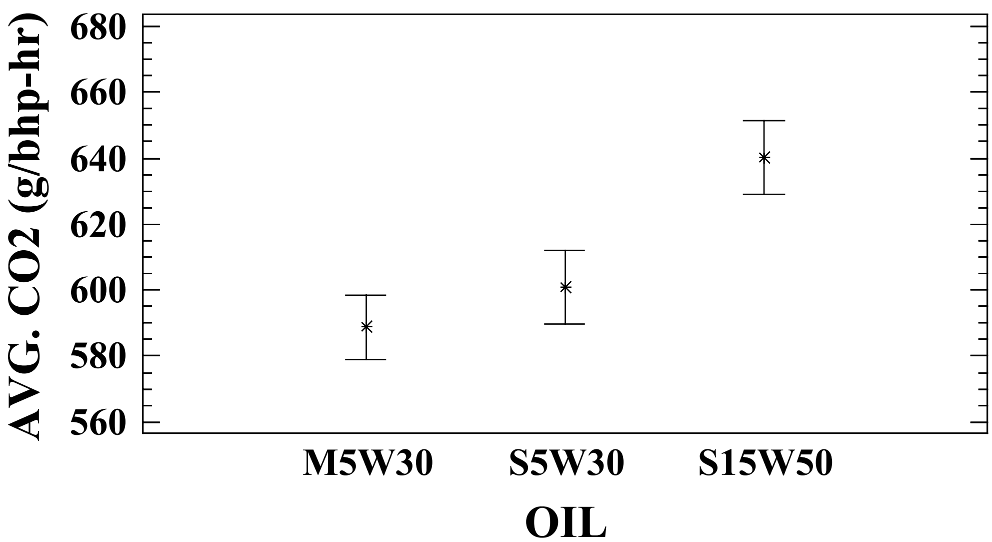


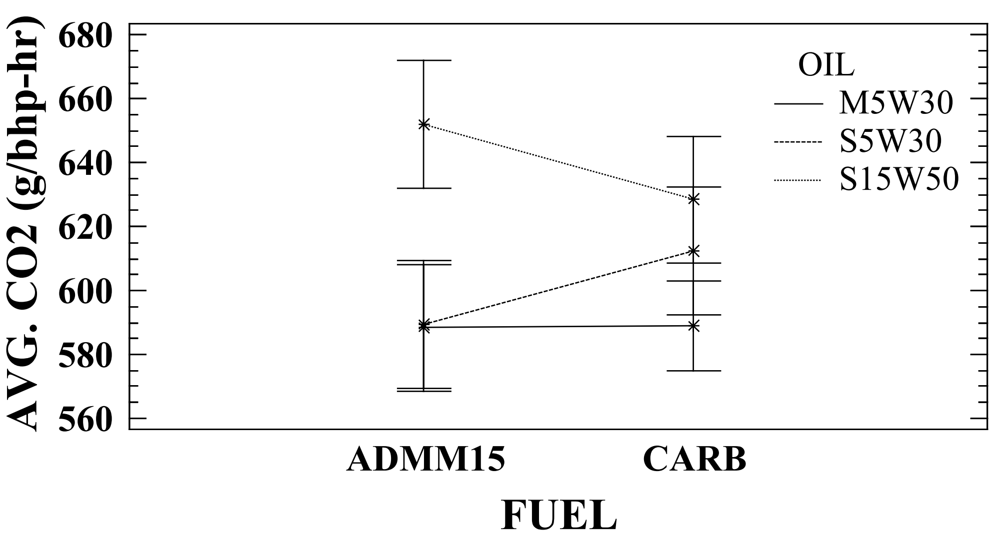




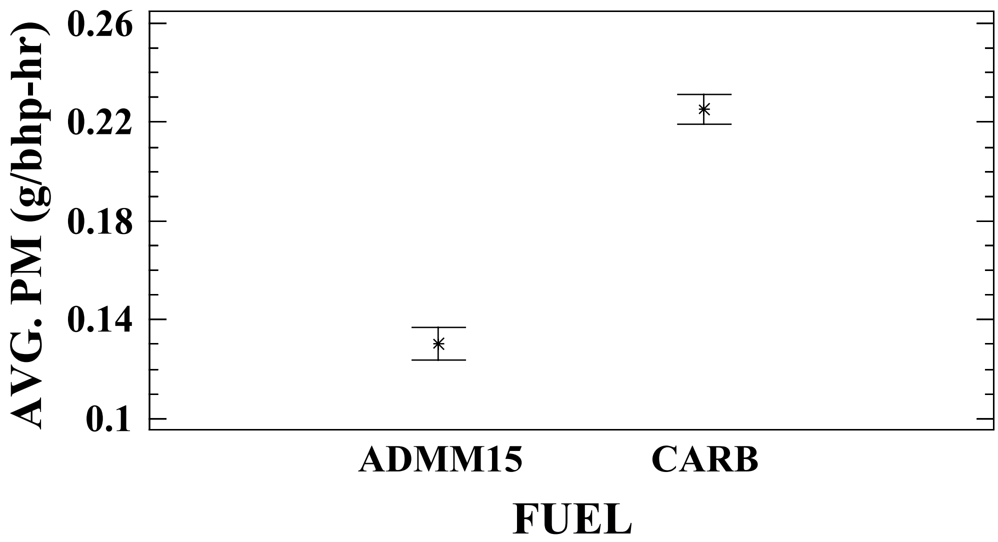
Mode 14 (4200 rpm, 158 ft-lb)
CO2

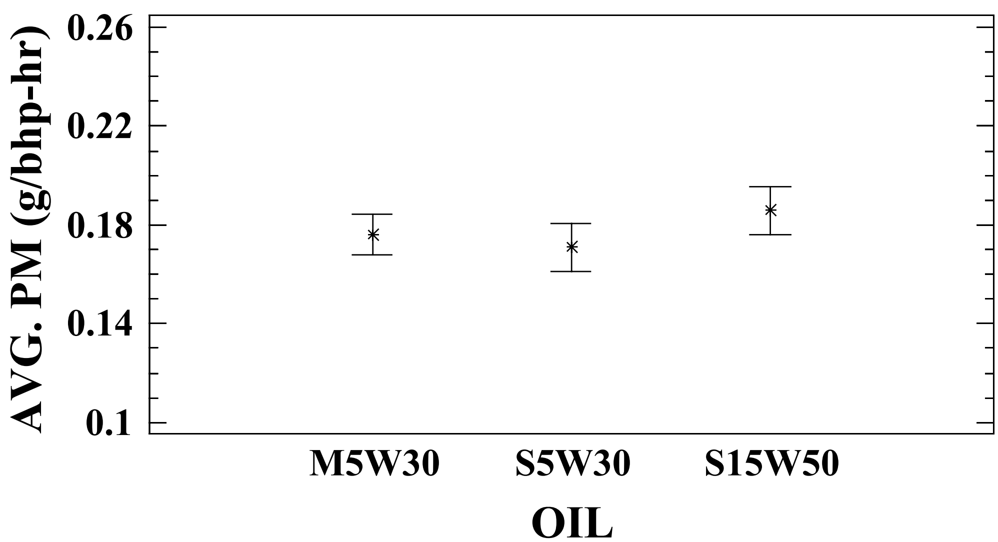


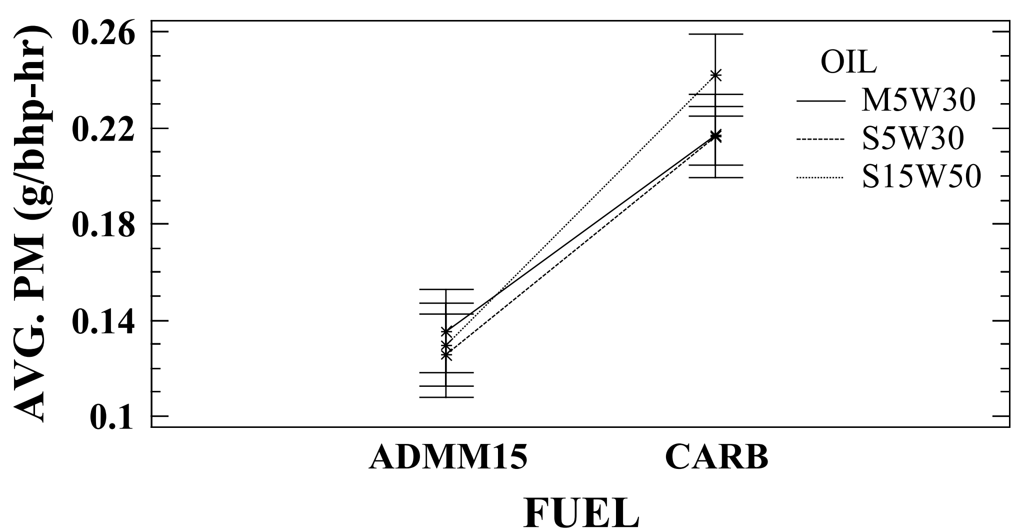




Weighted Steady-State Modes Particulate (PM)







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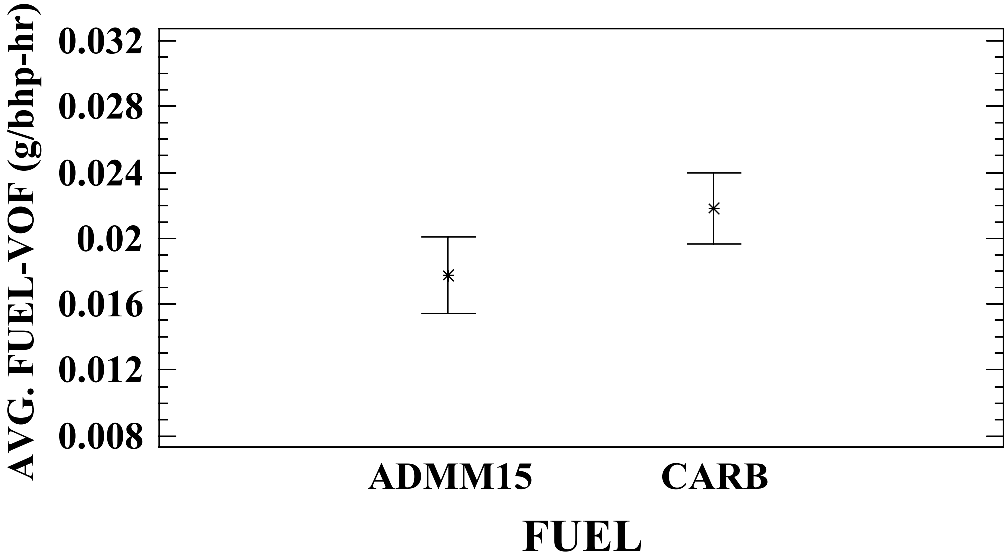
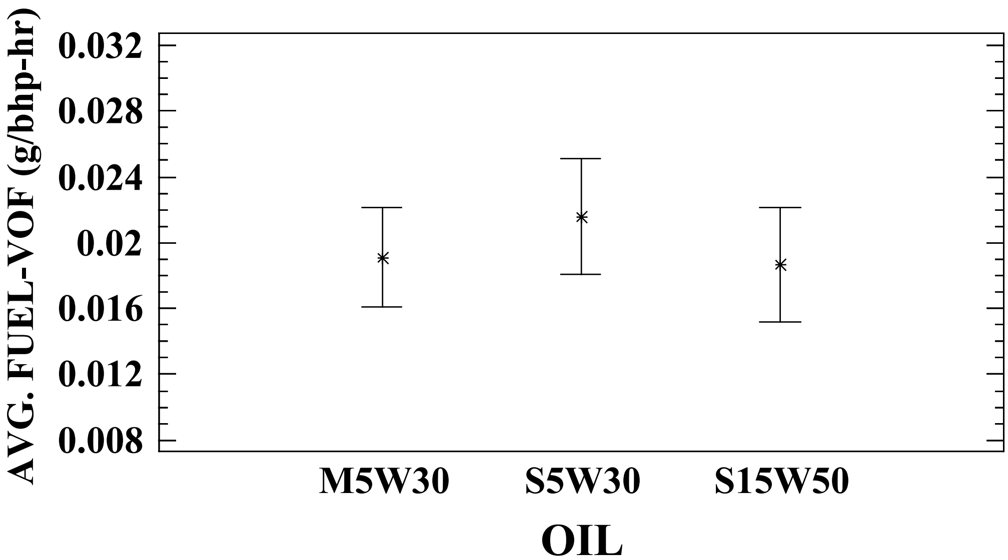
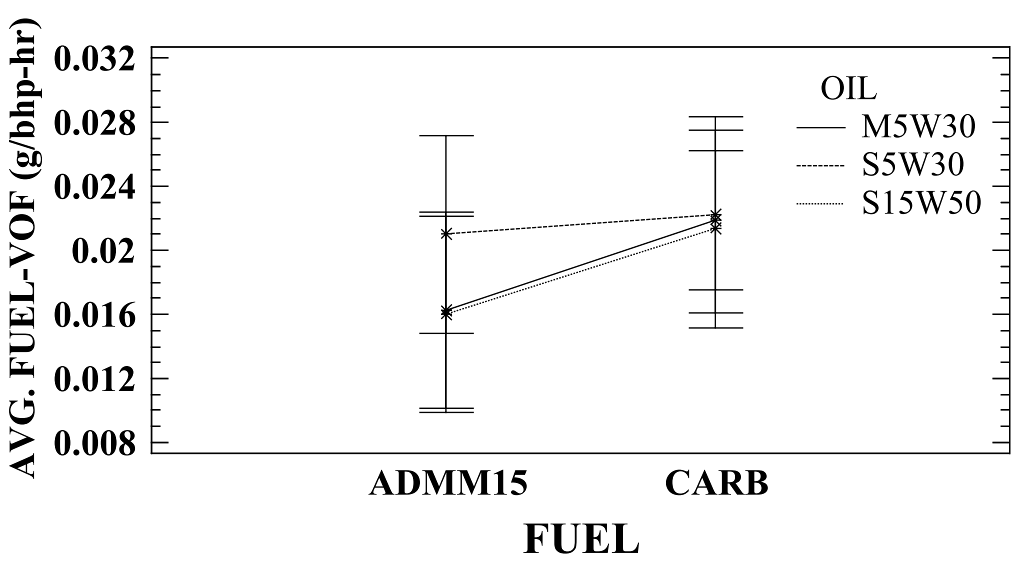
Fuel-VOF







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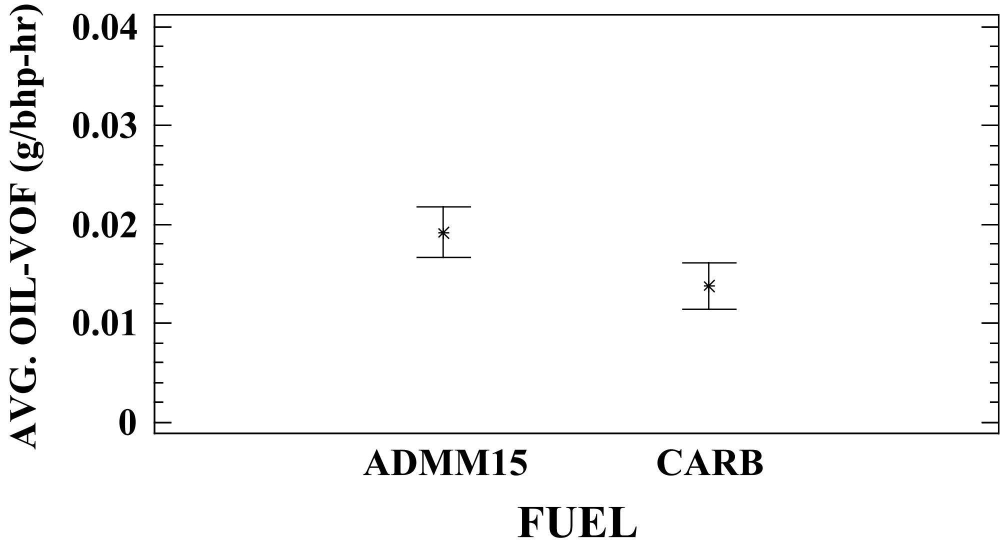
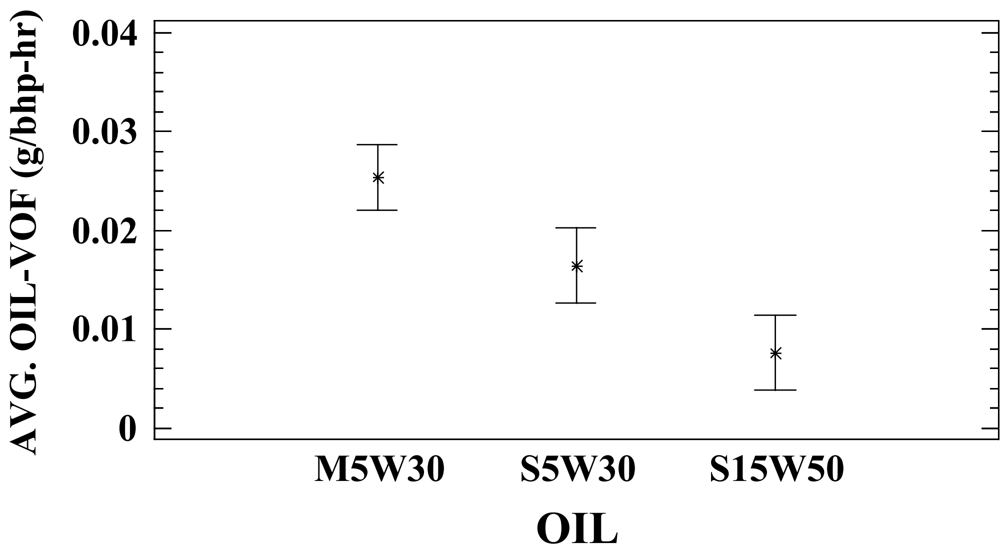
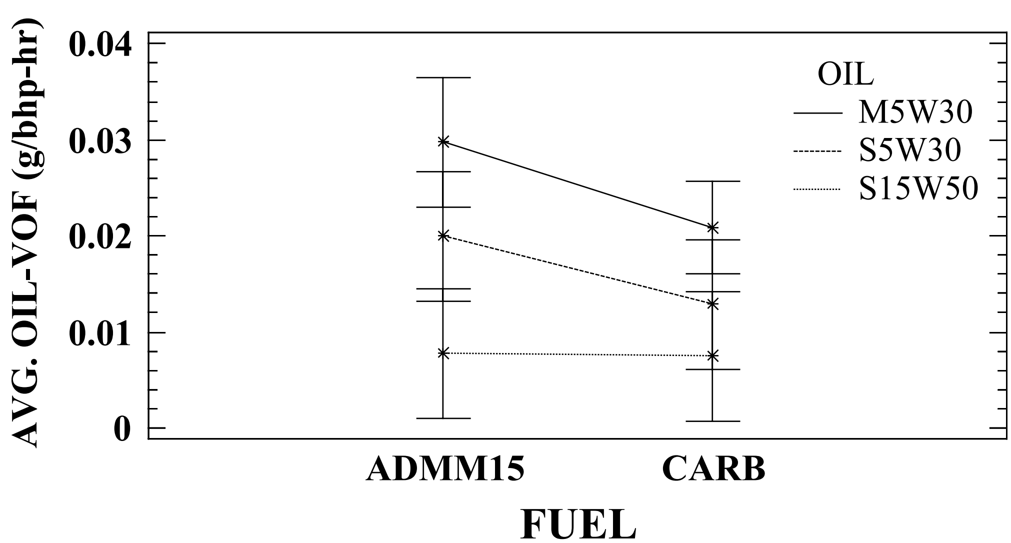
Oil-VOF







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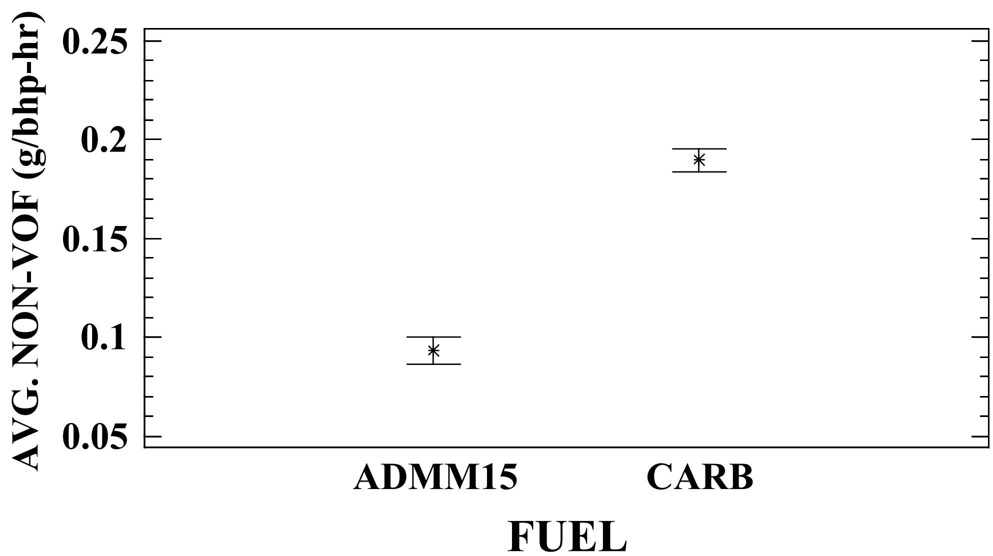
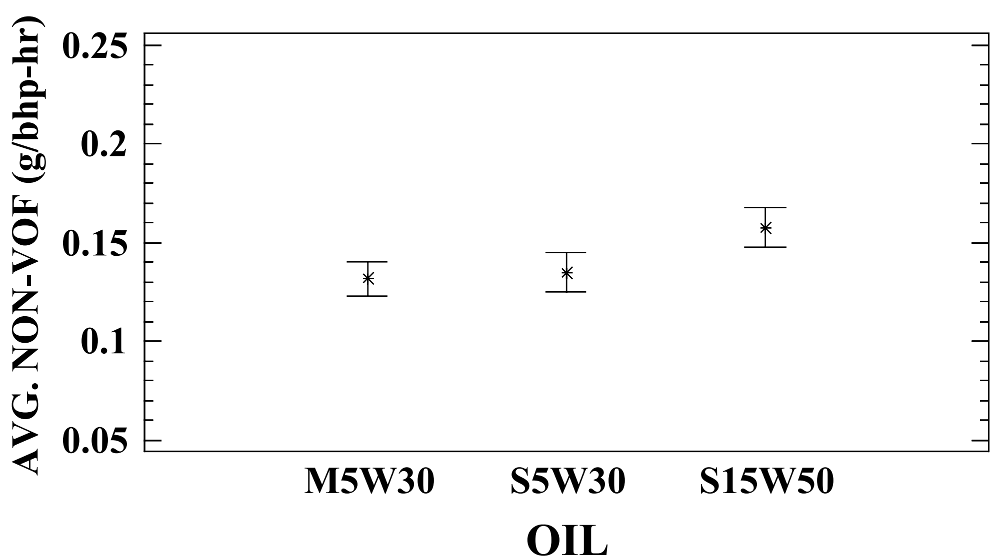
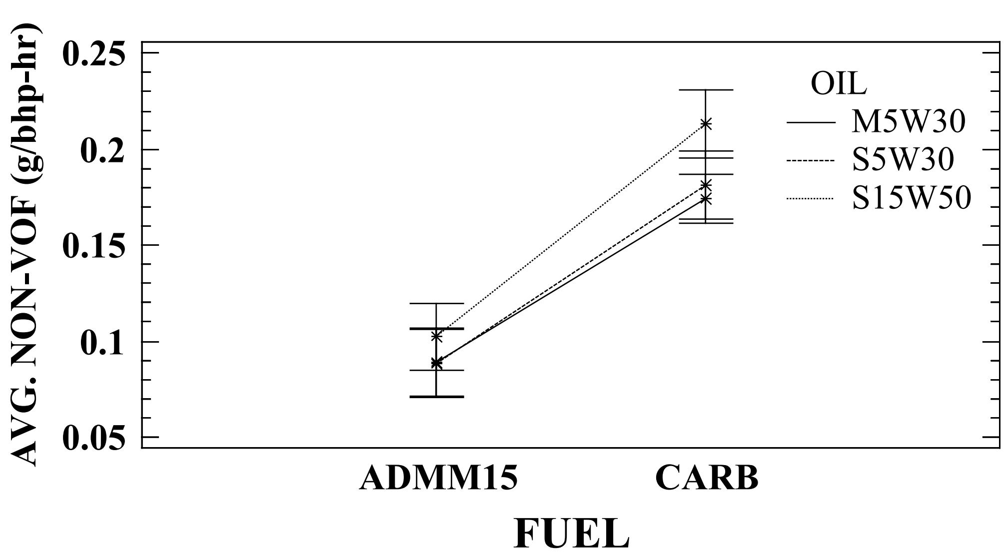
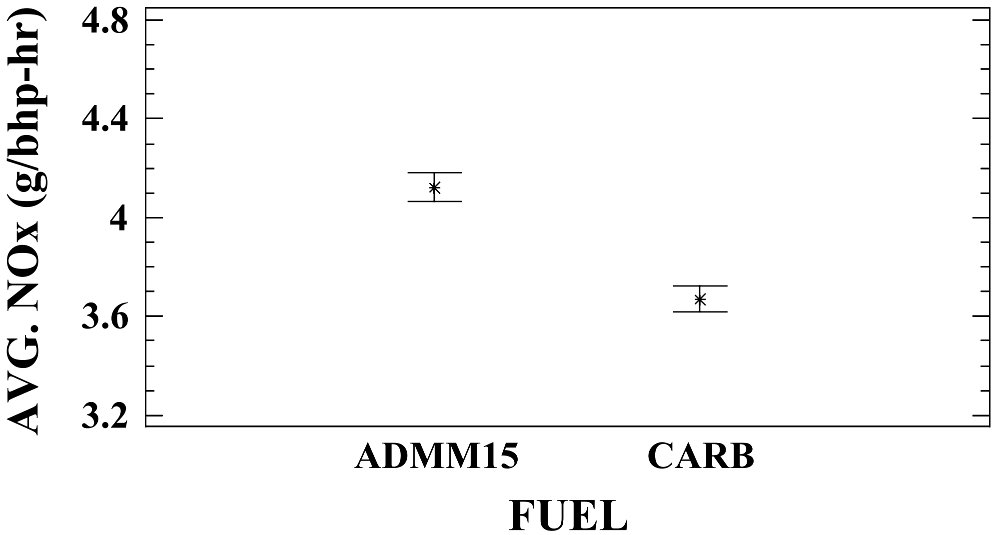
Non-VOF

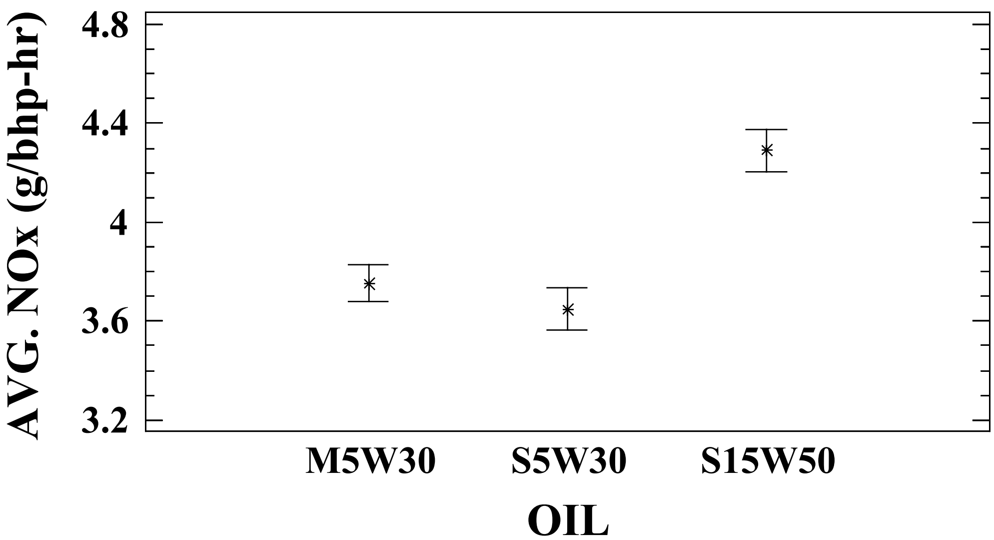


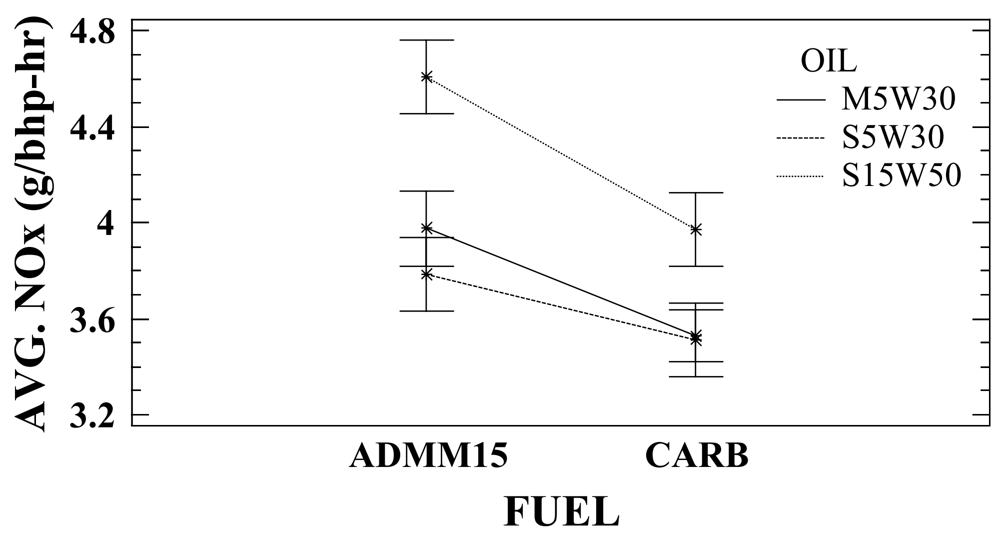




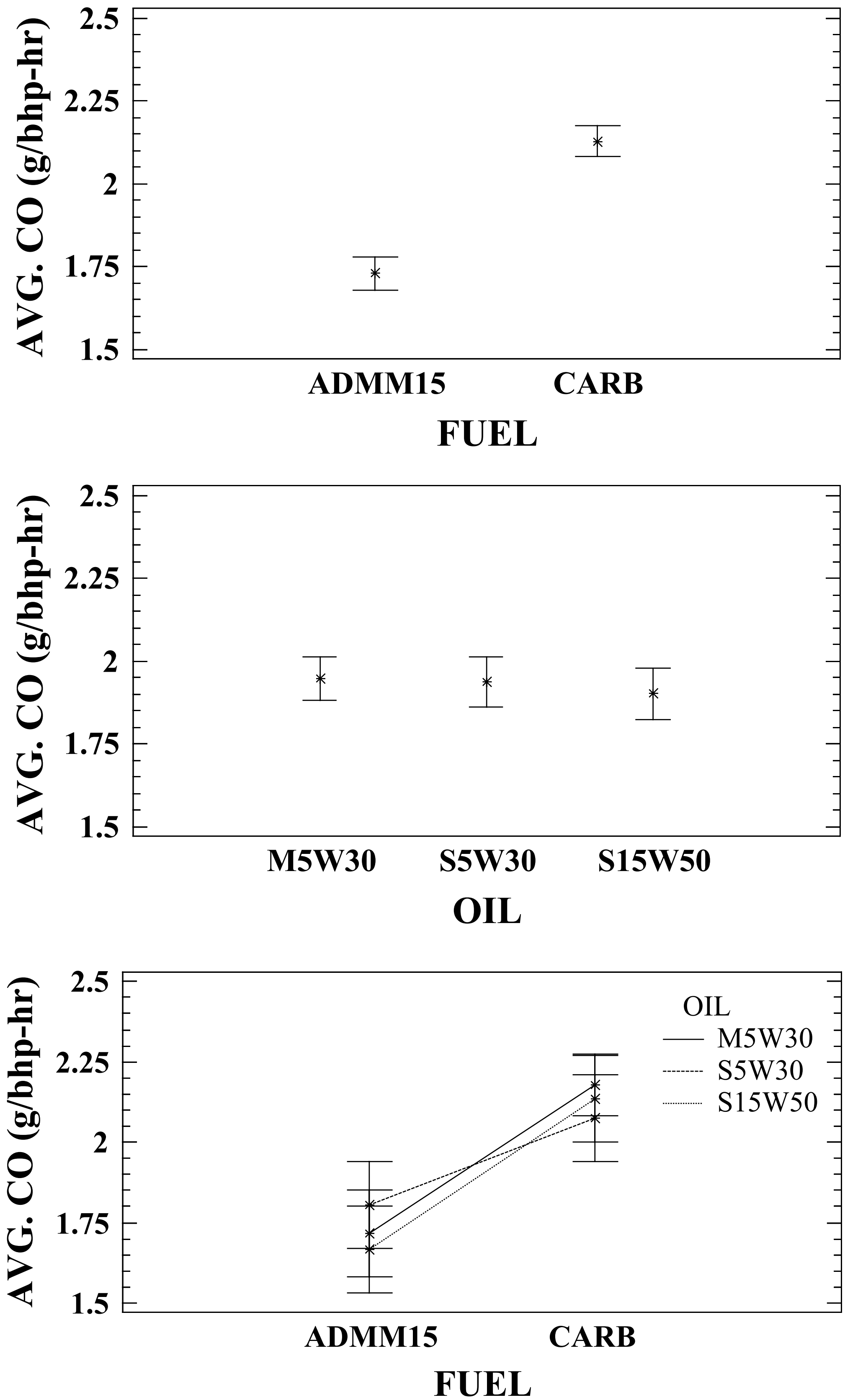
Weighted Steady-State Modes
NOx



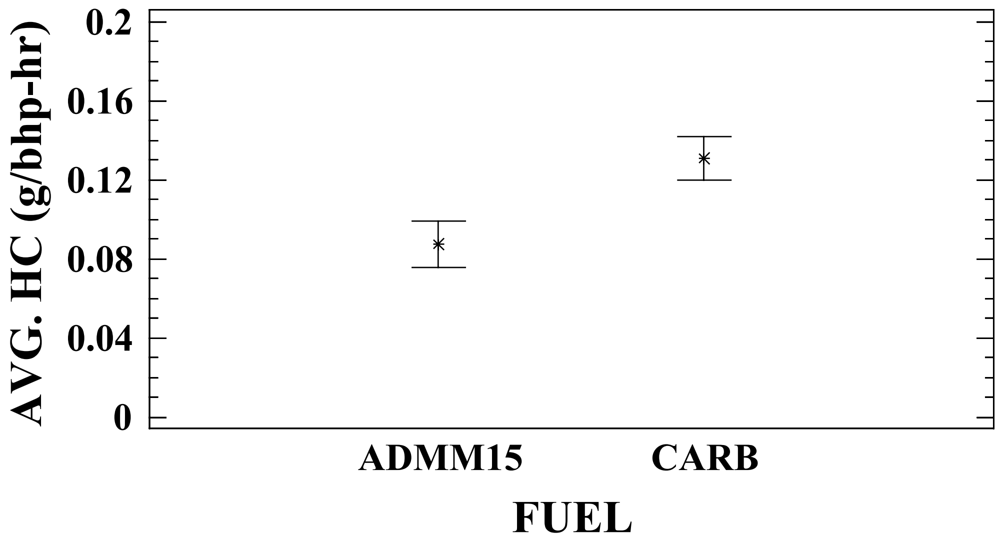


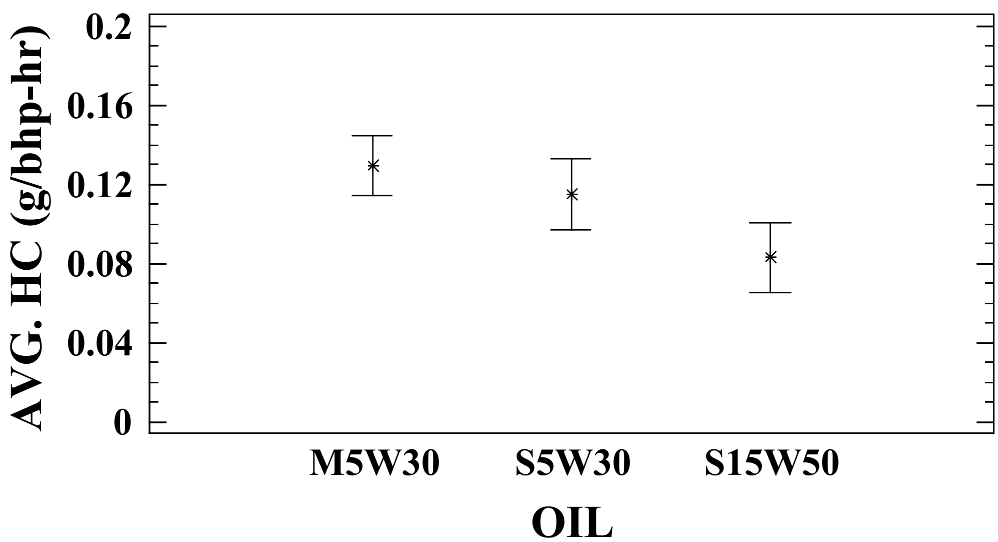


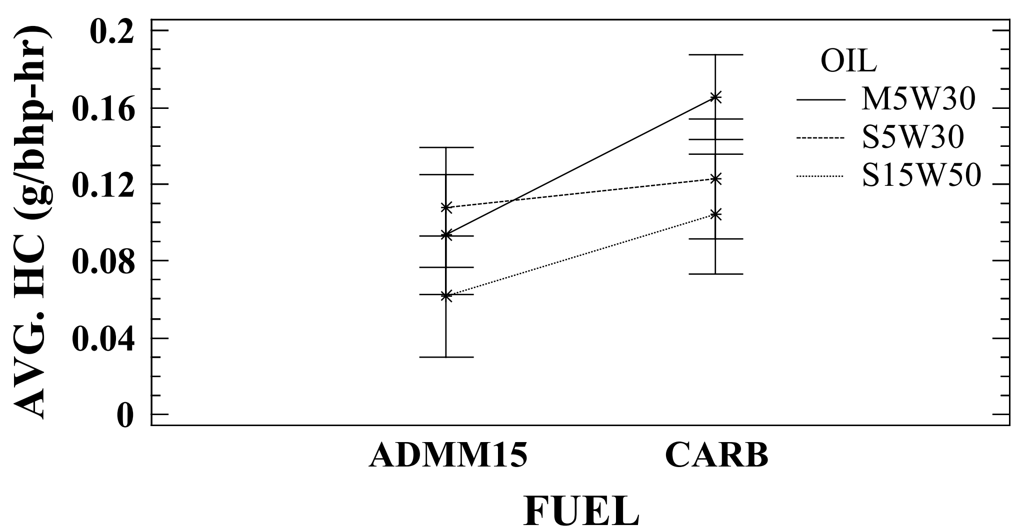
Weighted Steady-State Modes
CO



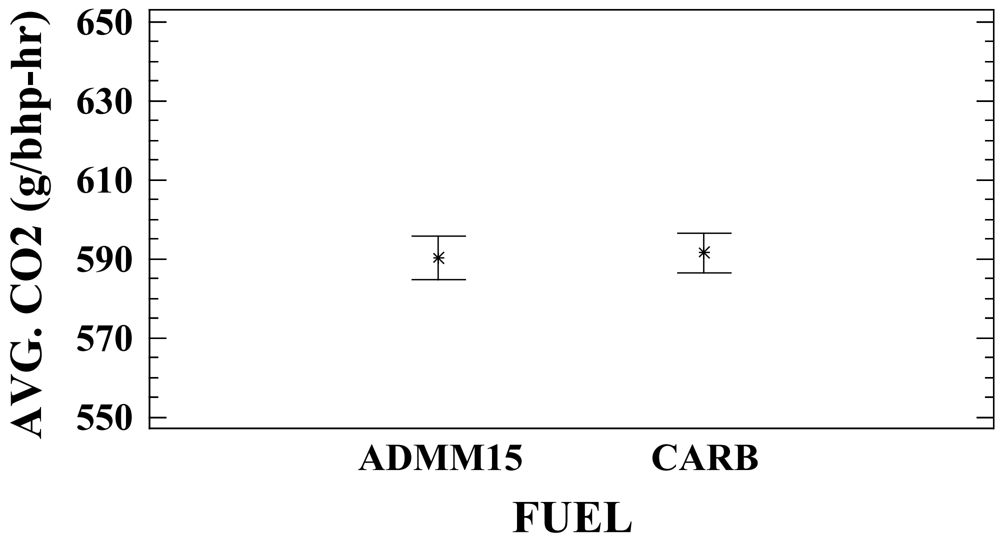
Weighted Steady-State Modes
HC

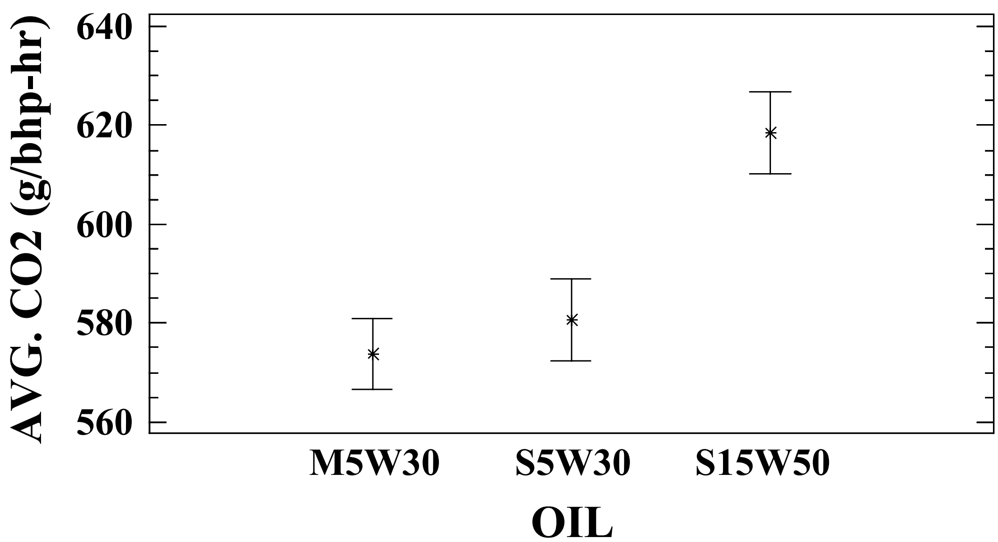


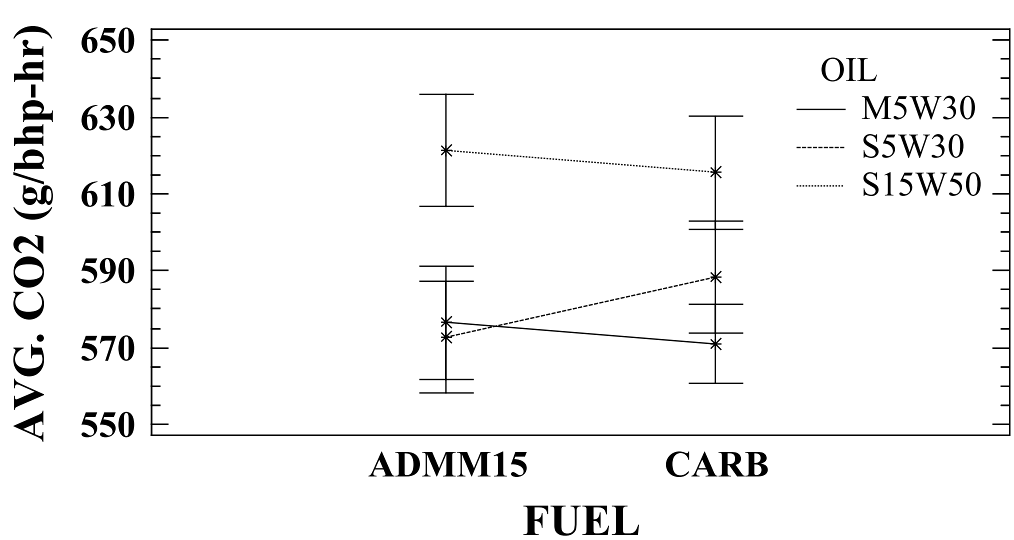




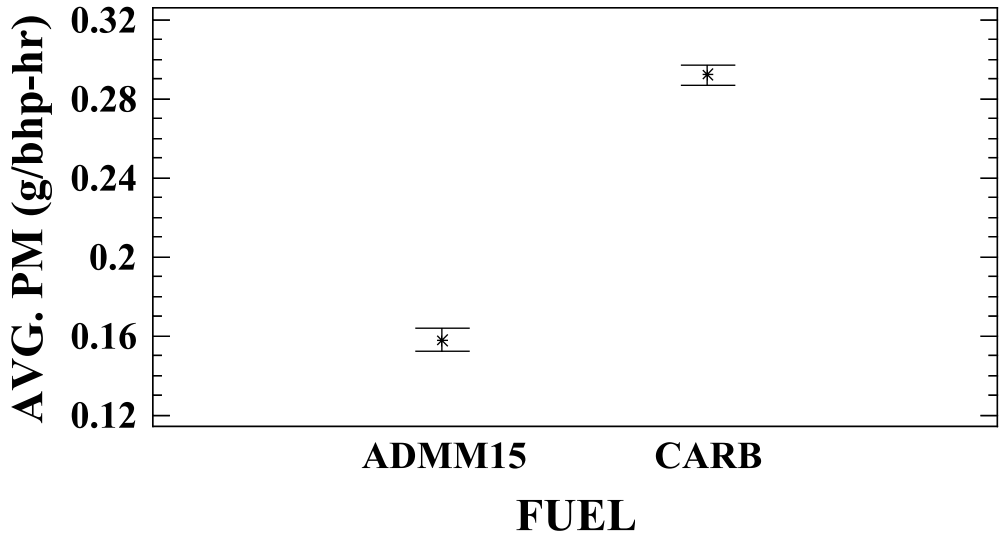
Weighted Steady-State Modes
CO2

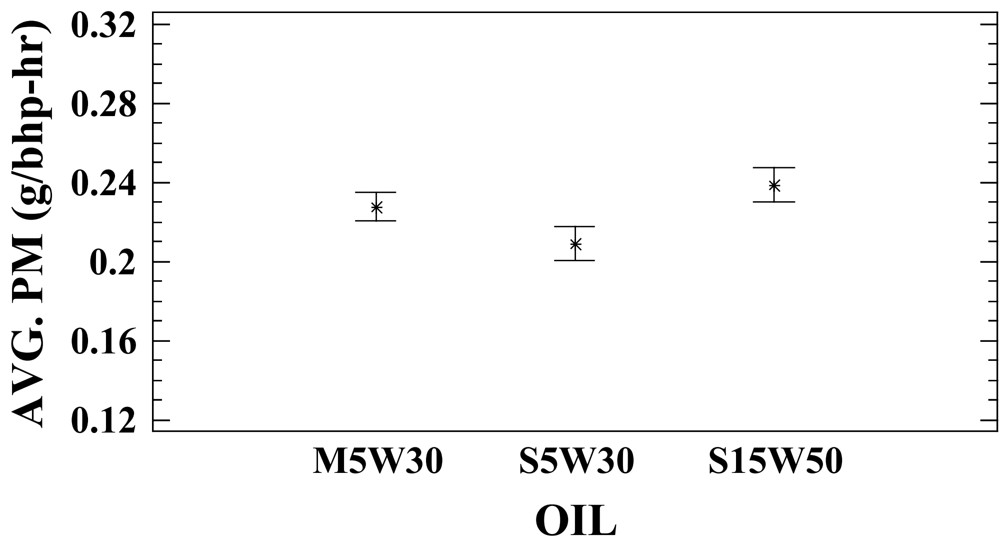


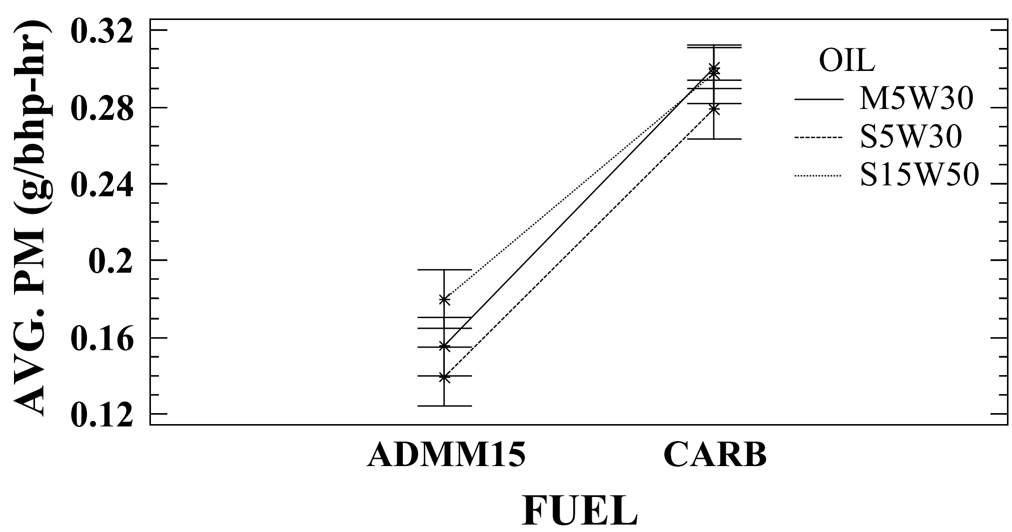




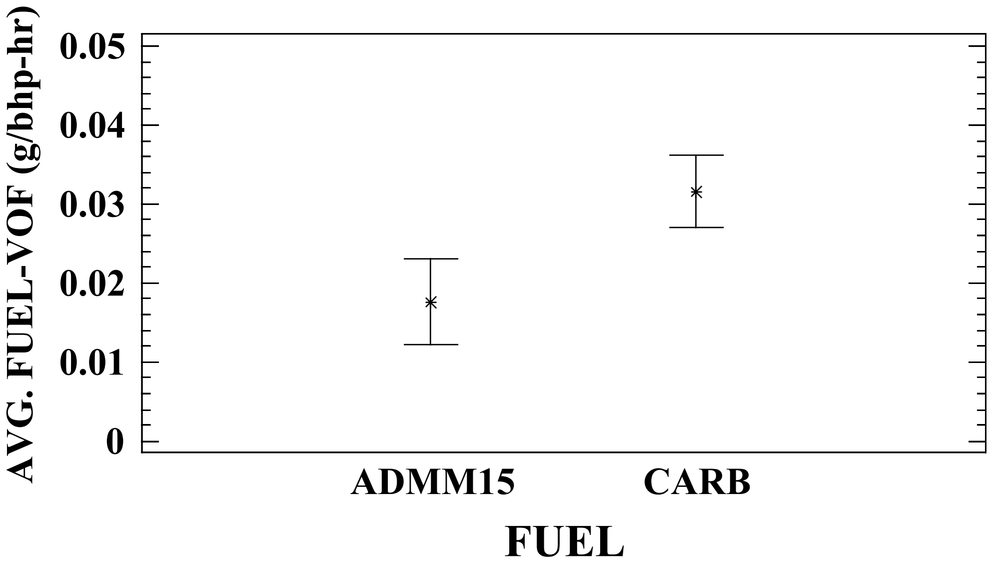
FTP-Transient
Particulate (PM)

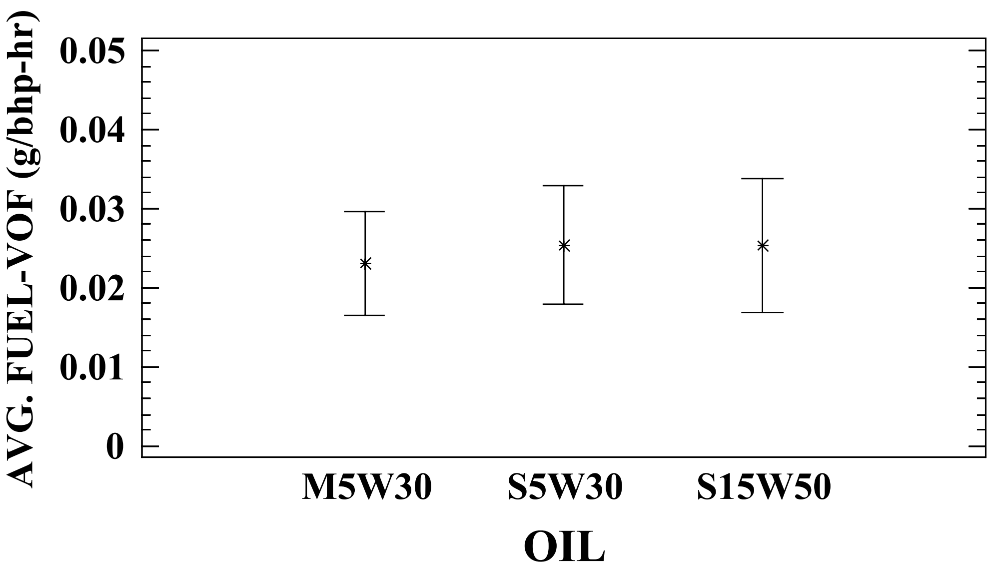


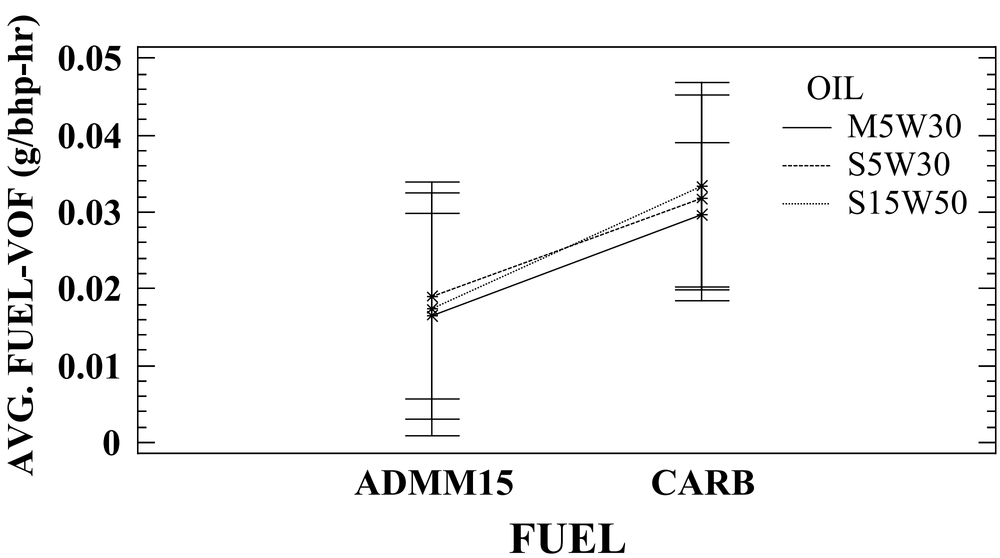




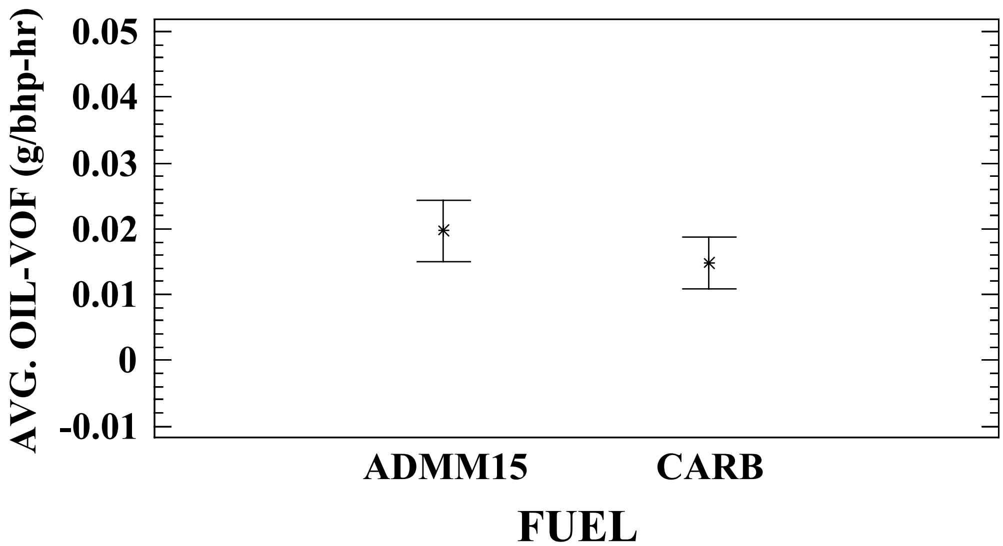
FTP-Transient
Fuel-VOF

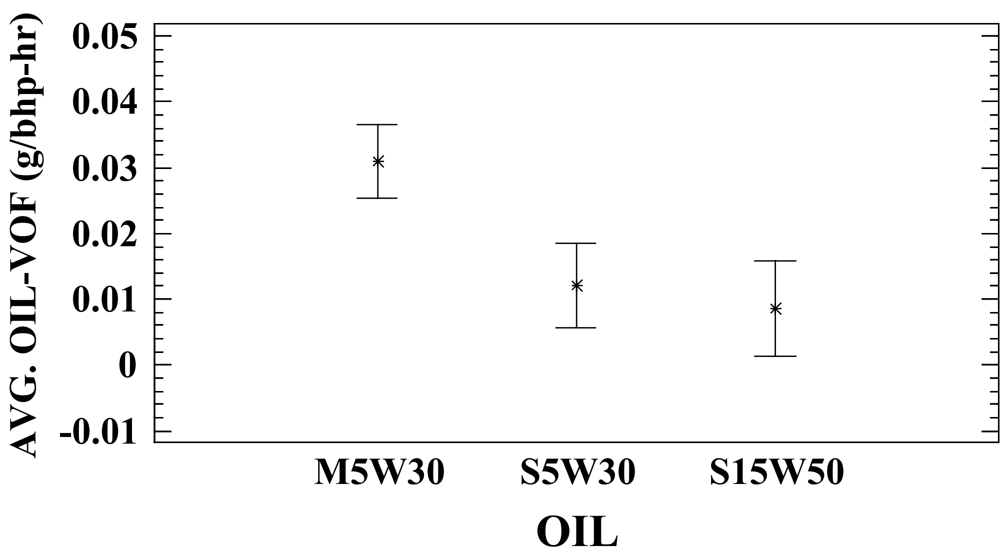


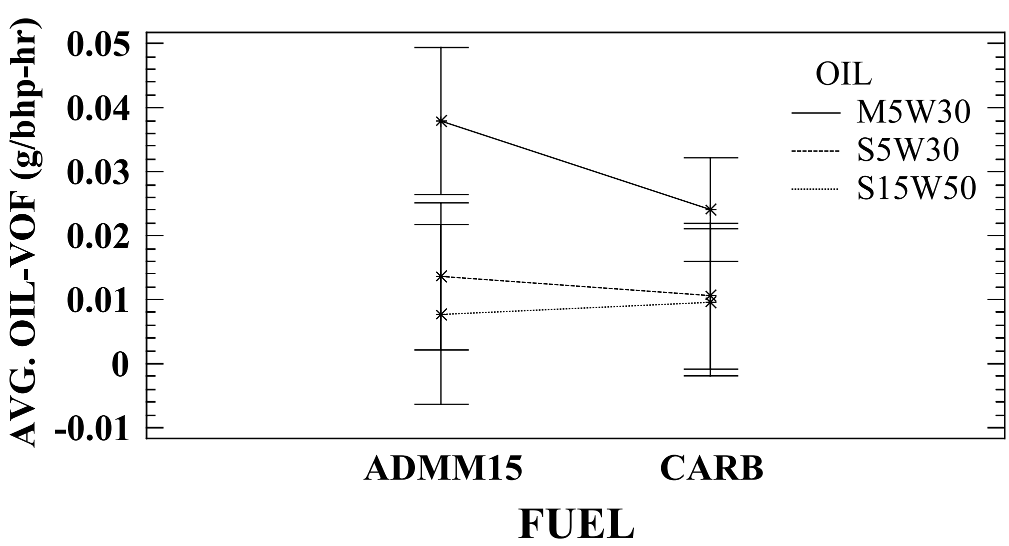




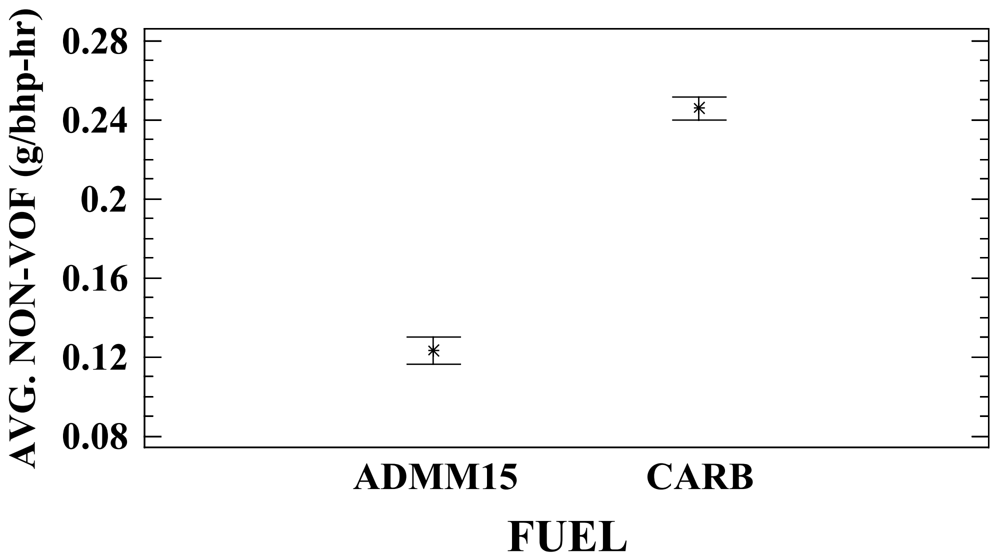
FTP-Transient
Oil-VOF

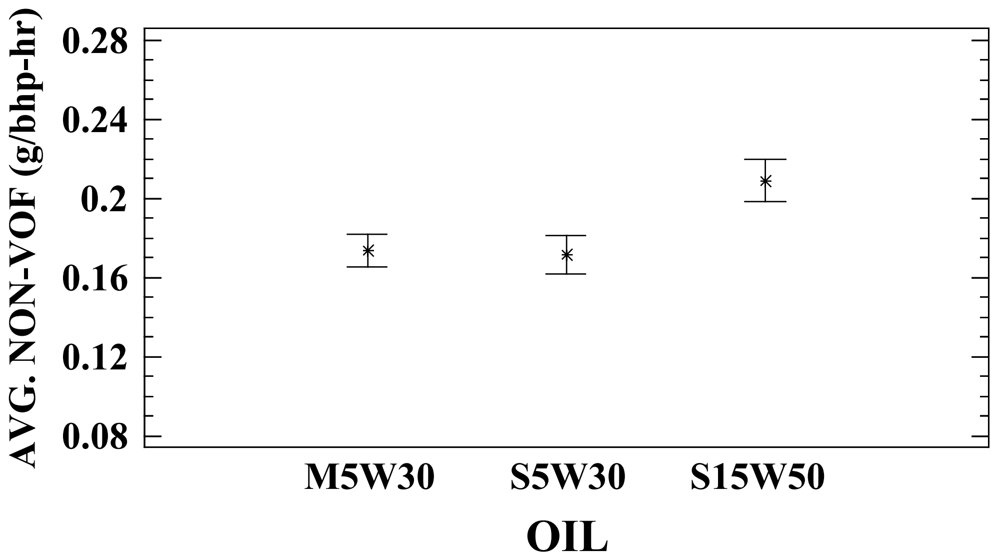


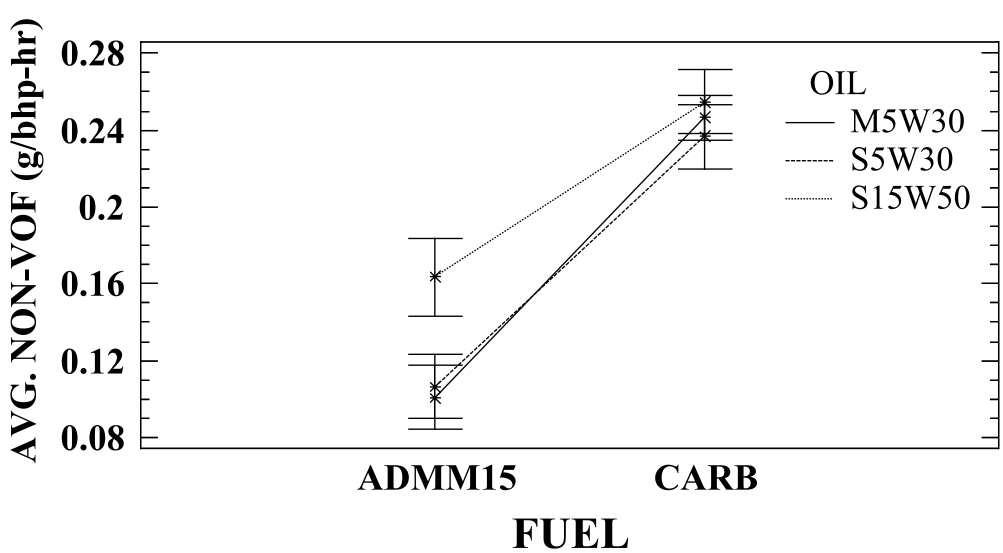




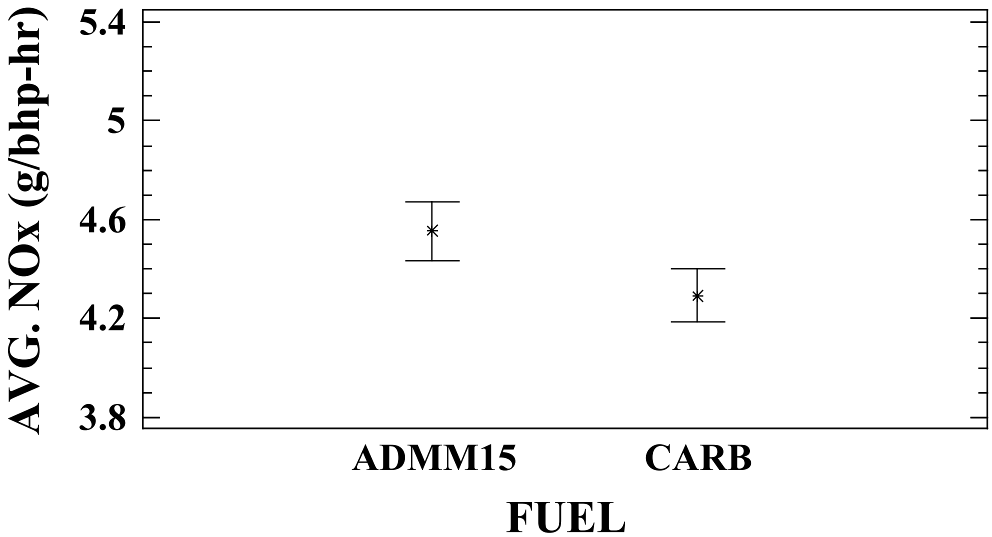
FTP-Transient
Non-VOF

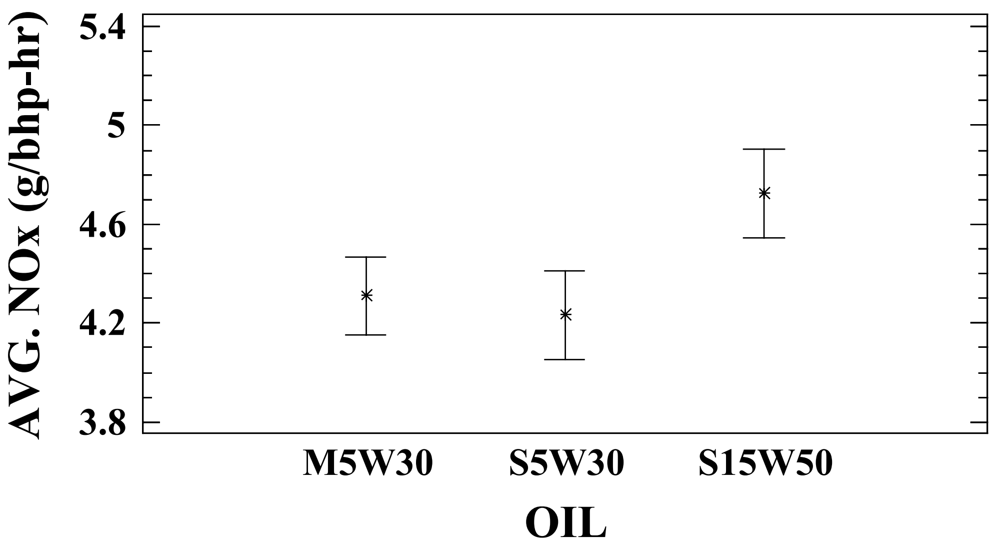


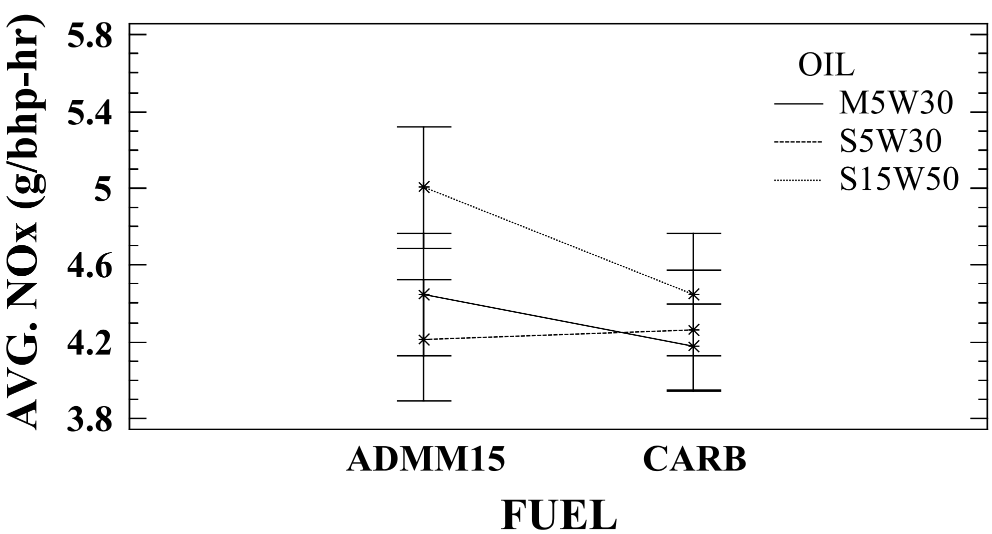




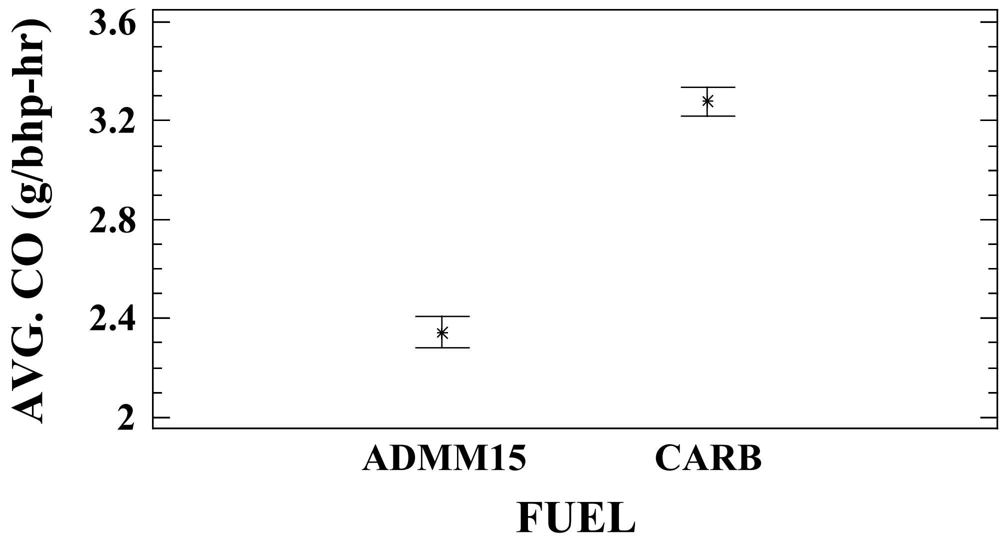
FTP-Transient
NOx

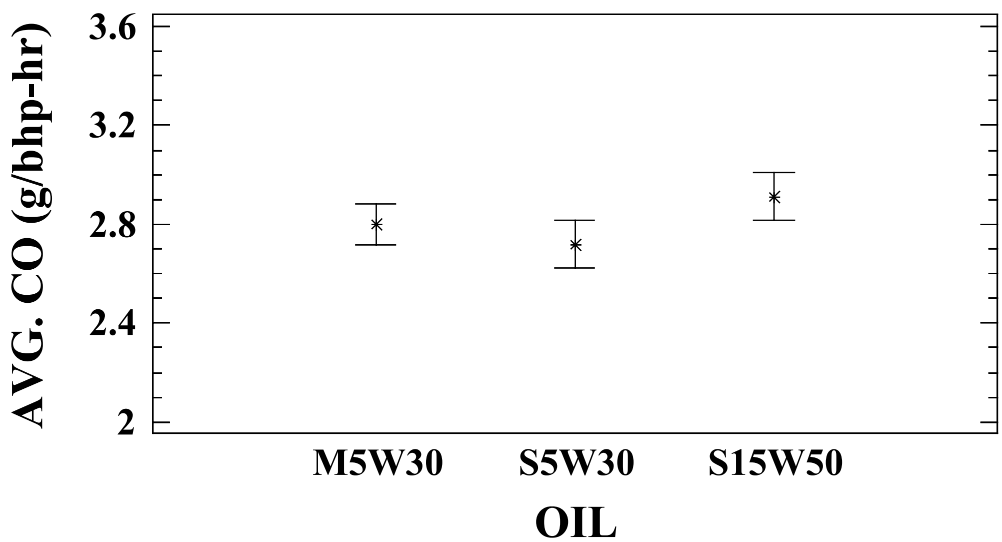


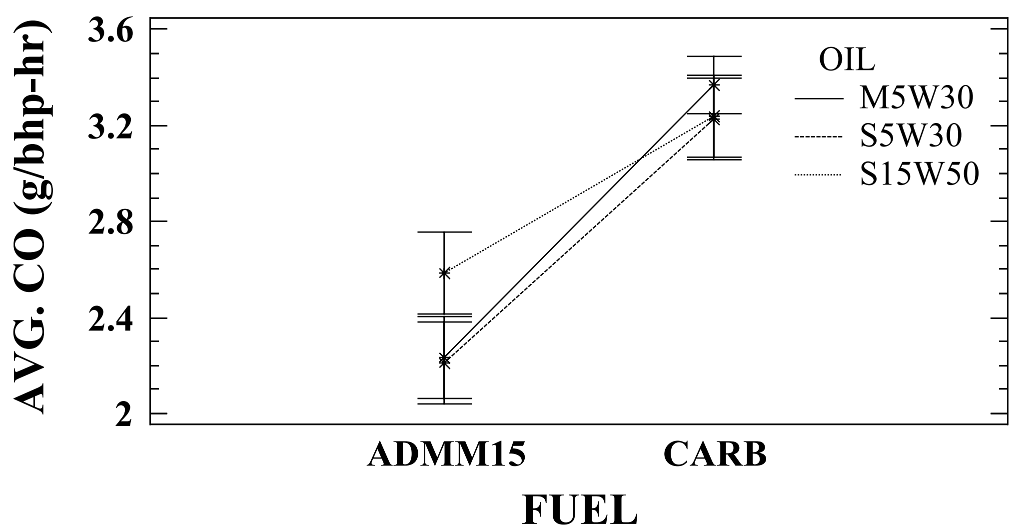




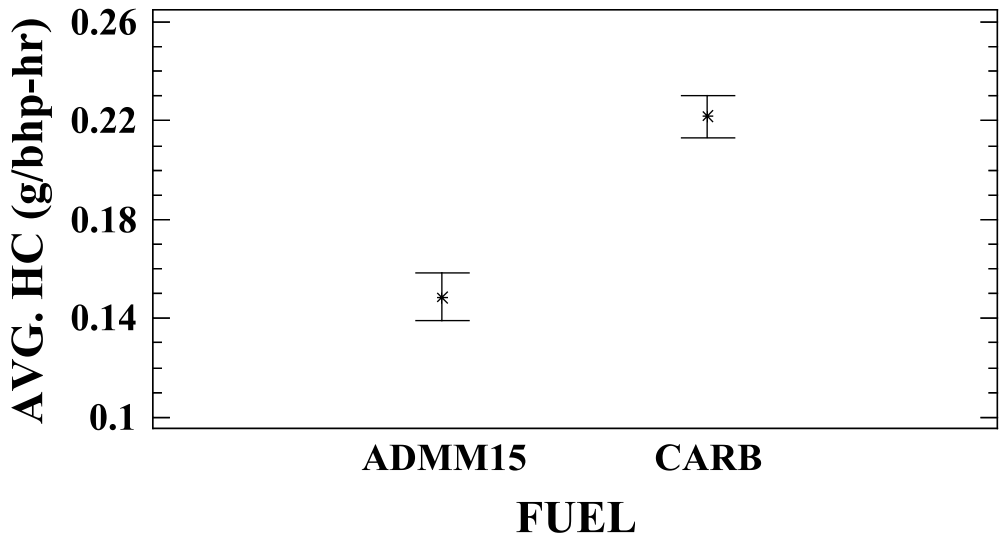
FTP-Transient
CO

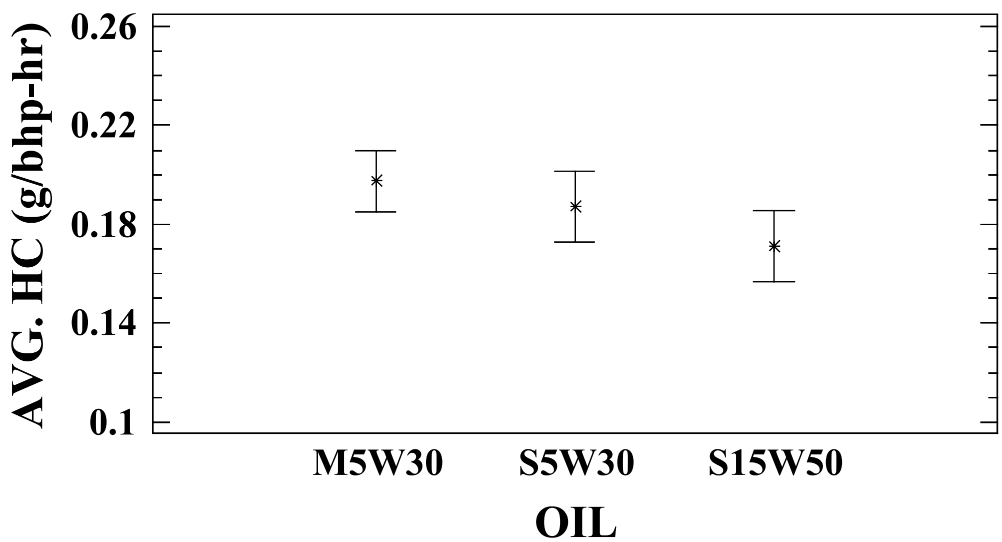


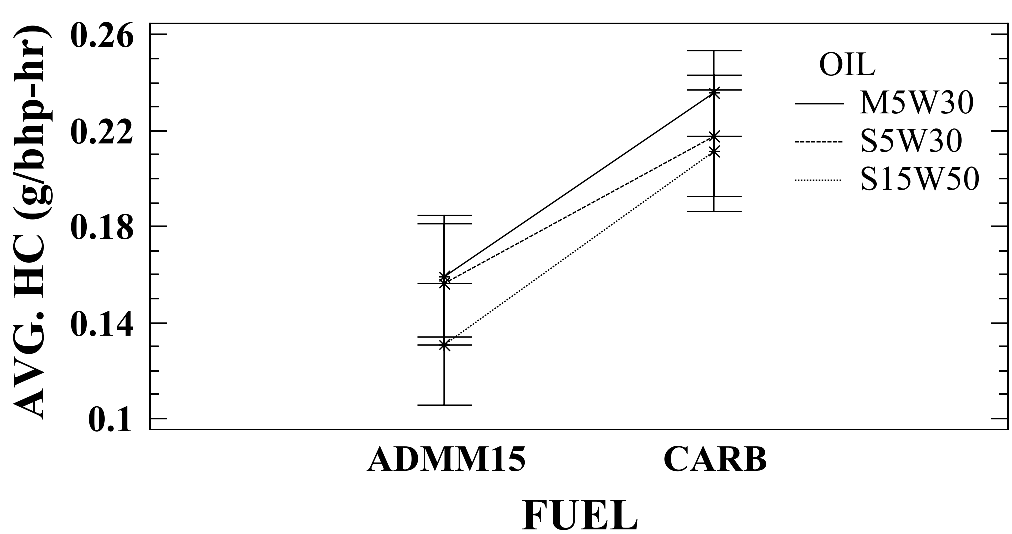




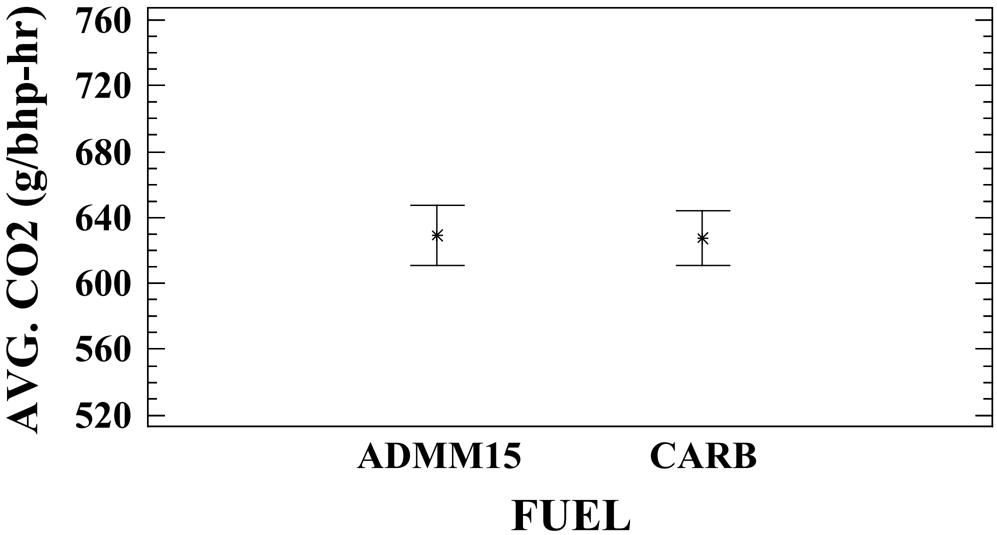
FTP-Transient
HC

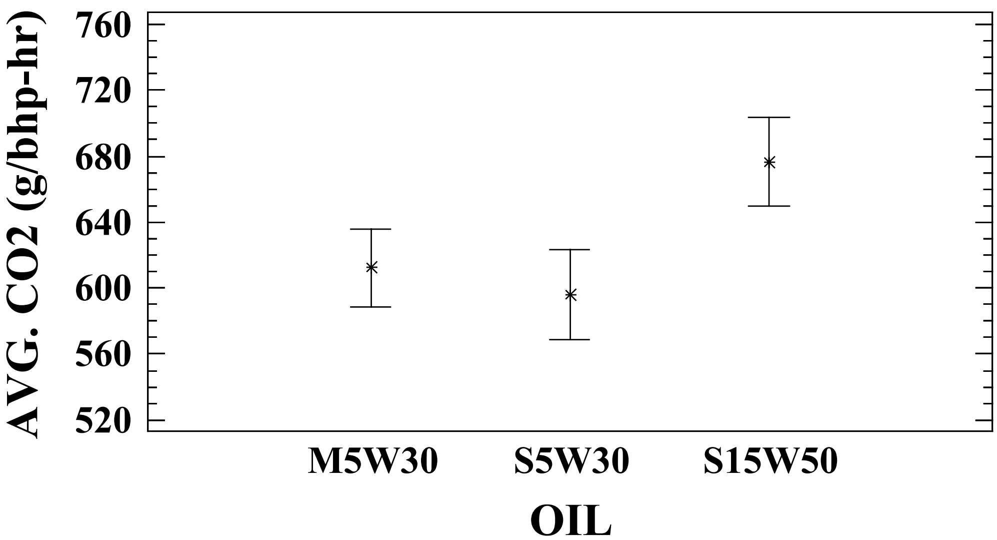


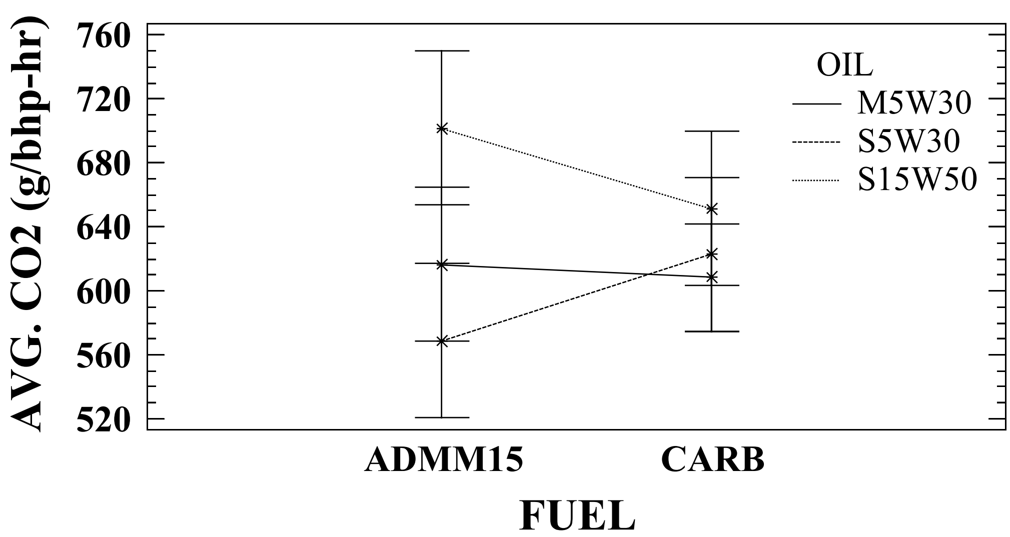




FTP-Transient
CO2







Appendix C
Least Squares Means By Mode

PM (90mm),g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0.0913	0.1538	0.1344	0.1166	0.1167
10	0.2226	0.2734	0.2671	0.2587	0.2181
5	0.0854	0.2068	0.1572	0.1556	0.1256
17	0.0906	0.2045	0.1082	0.1083	0.2261
14	0.2136	0.2873	0.2136	0.2157	0.2428
Transient	0.1581	0.2922	0.2278	0.209	0.2386
Weighted	0.1301	0.2252	0.1761	0.171	0.1859

FUEL-VOF, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0.0131	0.0175	0.0151	0.0168	0.014
10	0.0407	0.039	0.0414	0.0463	0.0318
5	0.0135	0.0189	0.0158	0.0172	0.0155
17	0.0081	0.0156	0.01	0.011	0.0146
14	0.0116	0.0181	0.0131	0.0148	0.0165
Transient	0.0176	0.0316	0.0231	0.0254	0.0254
Weighted	0.0178	0.0218	0.0191	0.0216	0.0187

OIL-VOF, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0.0055	0.0049	0.007	0.0057	0.0028
10	0.061	0.047	0.083	0.0585	0.0206
5	0.0232	0.0129	0.0295	0.0138	0.0108
17	0.0018	0.0011	0.002	0.0012	0.001
14	0.0032	0.0027	0.005	0.002	0.0019
Transient	0.0197	0.0147	0.0309	0.0121	0.0086
Weighted	0.0192	0.0137	0.0253	0.0164	0.0076

NON-VOF, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0.0727	0.1314	0.1123	0.0942	0.0997
10	0.121	0.1874	0.1428	0.1542	0.1657
5	0.0479	0.1749	0.1119	0.1233	0.0992
17	0.0808	0.1878	0.0961	0.0963	0.2105
14	0.1469	0.2666	0.1955	0.1988	0.2259
Transient	0.1235	0.2459	0.1736	0.1715	0.2091
Weighted	0.0932	0.1896	0.1317	0.1349	0.1577

CO, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0.6621	0.6402	0.6935	0.6031	0.6567
10	5.3743	6.5943	6.4287	6.4375	5.0867
5	0.8334	0.9789	0.9147	0.909	0.8948
17	0.9646	1.5519	0.8767	0.8875	2.0104
14	0.8128	0.8791	0.8229	0.856	0.859
Transient	2.343	3.2779	2.8008	2.7185	2.9121
Weighted	1.7294	2.1289	1.9473	1.9386	1.9015

NOx, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	6.7265	5.463	5.7765	5.3692	7.1386
10	1.3436	1.288	1.1821	1.1936	1.5718
5	3.4869	2.6947	2.8286	2.6487	3.795
17	4.0509	3.8393	4.0756	4.0946	3.665
14	5.0092	5.0657	4.8982	4.9341	5.2801
Transient	4.5525	4.2926	4.3099	4.2333	4.7244
Weighted	4.1234	3.6701	3.7522	3.648	4.2901

HC, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	0	0.0039	0.0057	0.0001	0
10	0.3544	0.566	0.5376	0.4899	0.3531
5	0.054	0.0578	0.0597	0.0555	0.0526
17	0.0138	0.0084	0.0199	0.0126	0.0008
14	0.0157	0.0186	0.0248	0.0181	0.0087
Transient	0.1486	0.2217	0.1974	0.1869	0.1711
Weighted	0.0876	0.1309	0.1296	0.1152	0.083

CO2, g/bhp-hr

Least Squares Means by Mode

	FUEL		OIL		
Mode	ADMM15	CARB	MINERAL 5W30	SYNTHETIC 5W30	SYNTHETIC 15W50
20	535.6006	543.603	538.304	531.6444	548.857
10	792.1285	780.3922	761.7174	765.3064	831.7572
5	506.2827	509.1966	495.1147	497.5932	530.5111
17	507.0154	514.5289	484.3617	507.1945	540.7603
14	609.9172	609.924	588.6976	600.8693	640.1951
Transient	629.0769	627.5688	612.3682	595.9255	676.6749
Weighted	590.1889	591.5289	573.6391	580.5216	618.4161

APPENDIX D

ENGINE OPERATING CONDITIONS

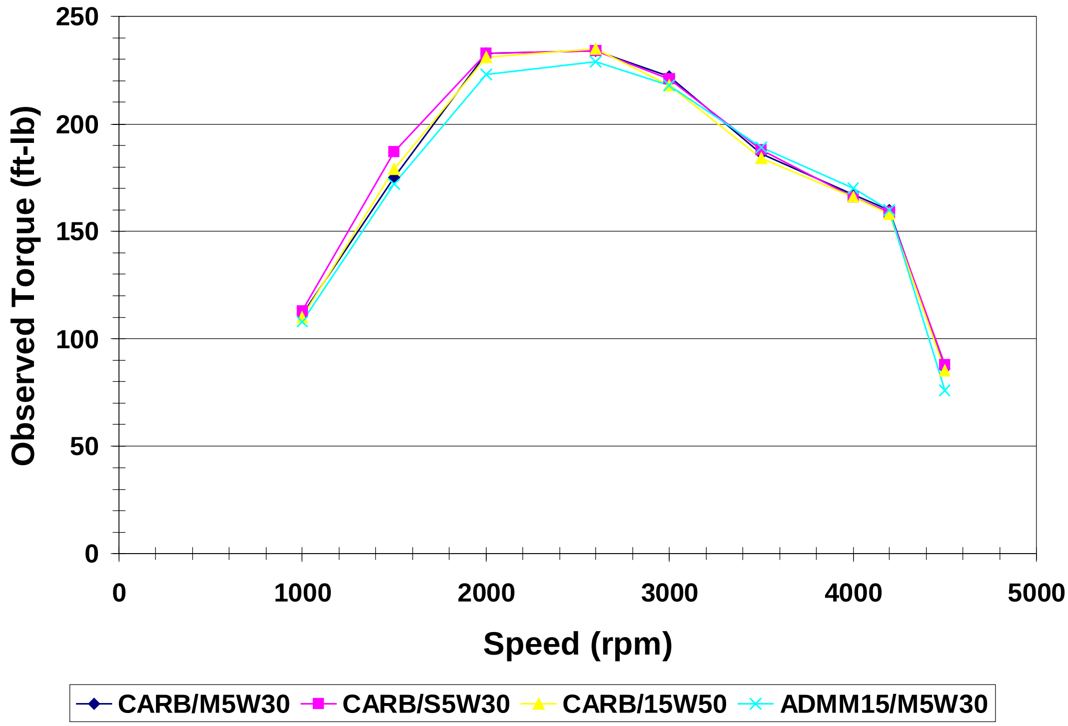


Figure D-1. Performance Data for Various Oils and Fuels

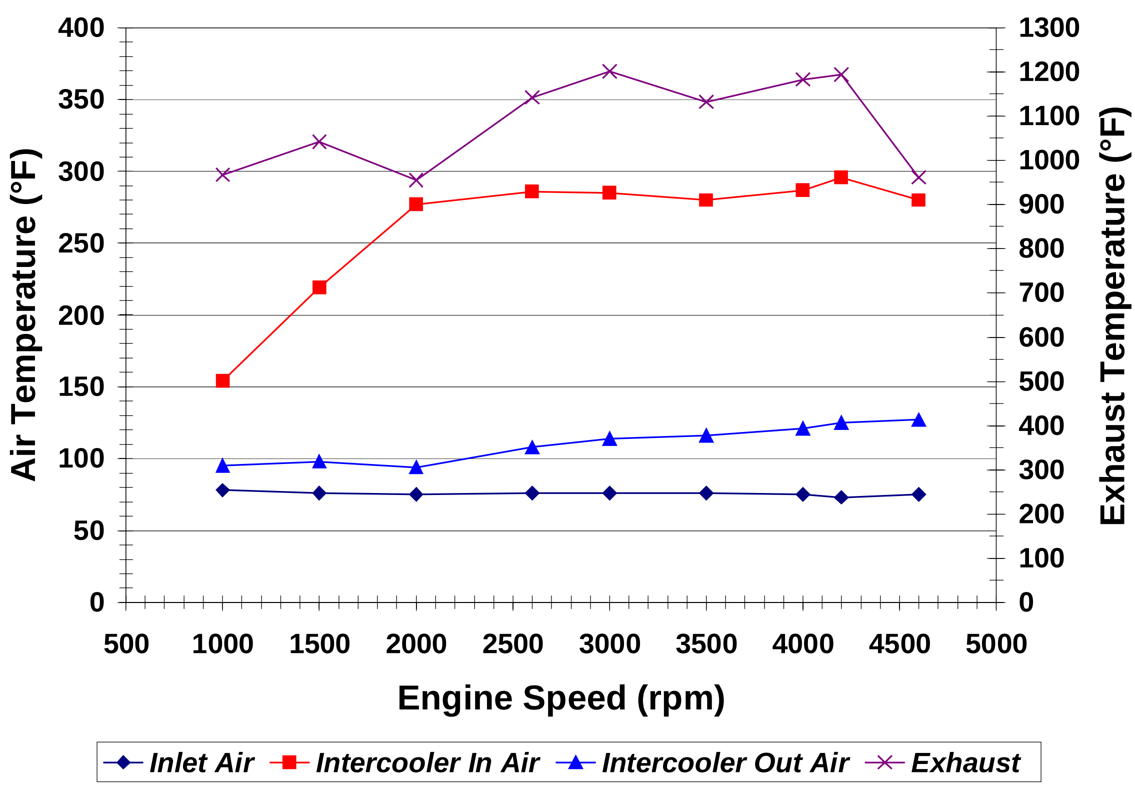


Figure D-2. Air and Exhaust Temperatures for Performance Test

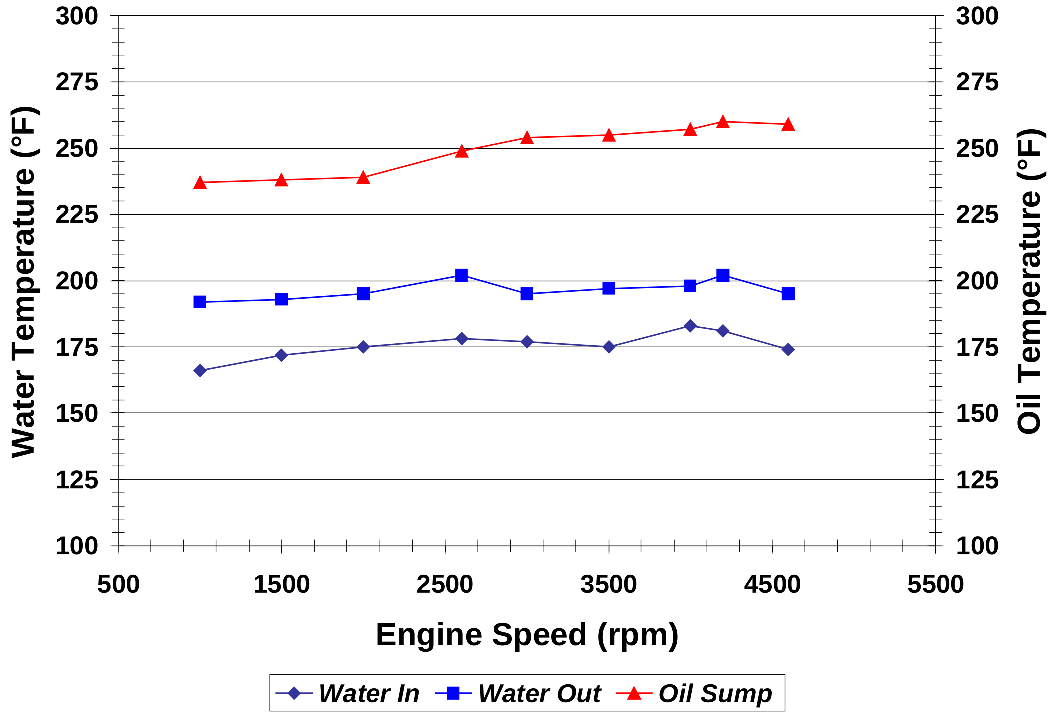


Figure D-3. Water and Oil Sump Temperatures for Performance Test

APPENDIX E
Turbocharger Failure

During the first day of the last baseline repeat, the engine failed.

The failure scenario is believed to be as follows:

1. Some mechanical part (valve, etc.) is impacting a blade of the turbine runner or over-speed, since this program is investigating conditions such as rated power and the FTP Transient, is simply causing a part of the turbine blade to break of. The net effect is the same: A part of a turbine blade brakes of.
2. The mechanical unbalanced turbine rotor now brakes in the middle of the shaft.
3. The compressor blade is now uncontrolled and it seizes against the compressor housing, and since this causes a resulting circumferential momentum on the runner, the runner bolt is spun of and thrown into the intake manifold.
4. The engine is shut down immediately.

This Appendix provides a series of pictures documenting the damage on the turbo charger.

Figure E-1: Compressor Runner and Housing.

Figure E-2: Zoom of Compressor Runner.

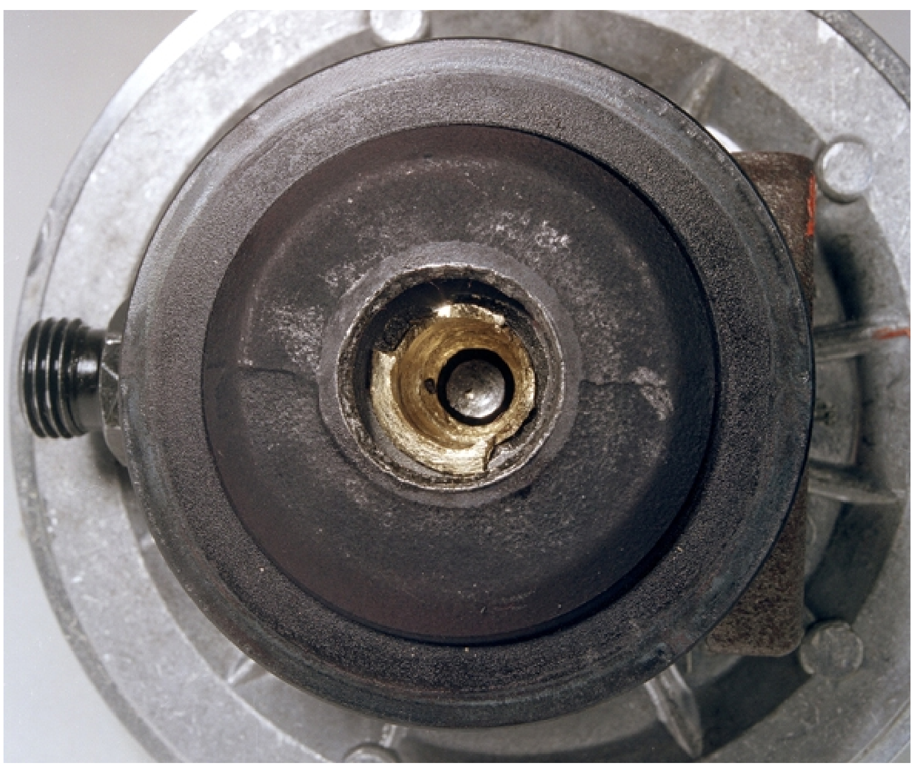


Figure E-3: Turbine Bearing.

Figure E-4: Missing Turbine Blade

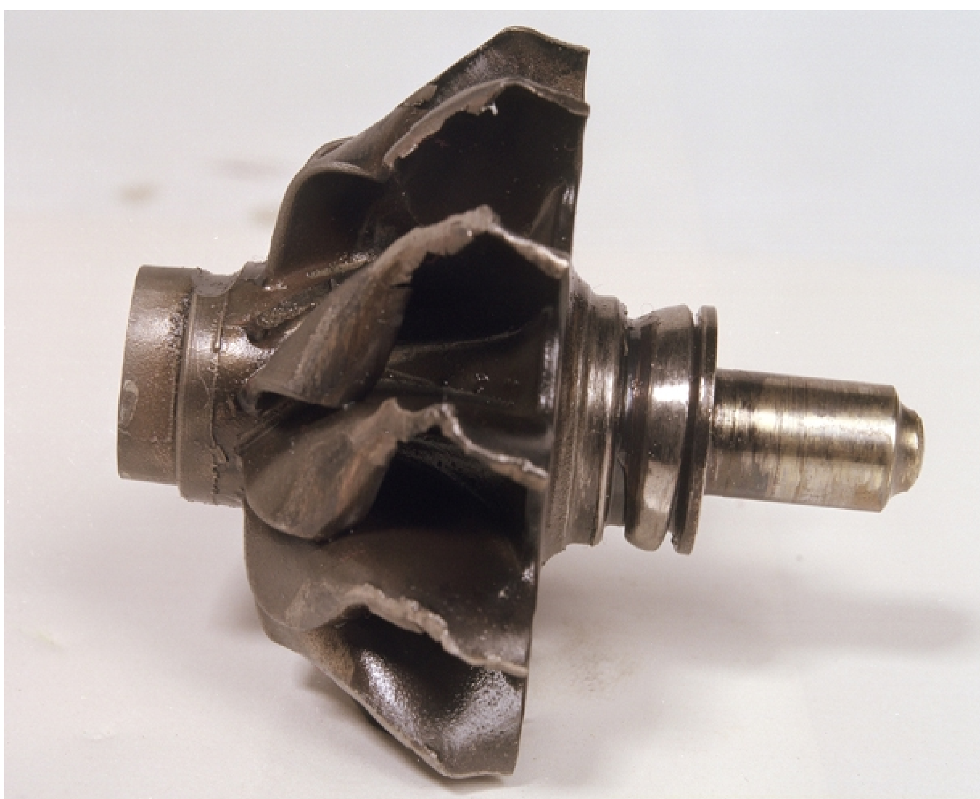


Figure E-5: Side-View of Turbine Runner.

APPENDIX F
PROCEDURE FOR DIGESTION AND ICP

Procedure for Digestion and ICP

1. The filters were cut in half and placed in pre cleaned Teflon PFA microwave digestion vessels.
2. 10 milliliters of trace-metals-grade concentrated nitric acid was added to each vessel. The vessels were capped and placed in our CEM MARS5 Microwave Accelerated Reaction System.
3. "Filter XP1500" was the microwave method employed. In this method, a power of 1200W is applied to ramp the temperature of the vessel contents to 240 degrees Celsius in 10 minutes and then held at that temperature for an additional 10 minutes.
4. Once the vessels cooled, the samples were quantitatively transferred to centrifuge tubes and brought up to a final volume of 50 milliliters with diwater.
5. The digestates were then analyzed by ICP.